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Our purpose: 100 yr of striving to deliver technical editorial excellence to the HPI

One hundred years ago, a group of individuals saw a need to disseminate the latest technologies and know-how to improve refining operations, safety, management and profitability. At the time, World War 1 had ended roughly 4 yr prior, and global gasoline demand expanded immensely. In turn, new refining capacity was being built around the world to increase production to satisfy burgeoning demand. Simultaneously, new discoveries were being made to produce plastics, fertilizers and other petrochemical products.

However, as with any growing industry, challenges emerged. In turn, these challenges brought forth the best in individuals, resulting in new technologies and products that revolutionized the world—a common theme within the hydrocarbon processing industry (HPI) even today. These ideas, technologies, know-how and problem-solving techniques have been the basis for *Hydrocarbon Processing* for 100 yr. The publication has and will continue to be written by the industry for the industry.

Origins. In September 1922, Gulf Publishing Co. (now Gulf Energy Information) launched Vol. 1, No. 1 of *The Refiner and Natural Gasoline Manufacturer.* The publication's name changed several times over the next few decades—and its coverage expanded to include petrochemicals and gas processing/LNG, as those industries evolved—until the name *Hydrocarbon Processing* was adopted in June 1966. The publication's title—*Hydrocarbon Processing*—represents the integration of the global refining and petrochemical industries and the technical processes and operational know-how that are synonymous with refinery and petrochemicals production.

The following is the publication's inaugural editorial comment, written by Gulf Publishing Co.'s President at the time, R. L. Dudley. Not only does he provide the basis of the publication's direction and audience, but also the intense focus on editorial integrity—a guideline that is strictly followed to this day.

Mr. Dudley's words laid the foundation for the genesis of what was to become the HPI's most trusted and read technical publication. These guidelines have resonated within the publication for 100 yr and continue to be the basis for technical editorial excellence.

OUR PURPOSE

The trade publication that attempts to cover a field when that field does not exist is doomed in advance; a publication that attempts to cover a field that does exist will prosper just in proportion to the earnestness of its purpose and the accuracy of its judgement.

For a long time, we have believed that the refining branch of the oil industry deserved a publication devoted to its particular challenges. For a long time, we have believed that the natural gasoline business had grown to the point where a publication dedicated to its interests was needed.

These two branches of the industry, closely allied in more ways than one, have developed to a tremendous degree during the past decade, but the development is by no means completed. For some time, we have thought that an industry that must get better results with the raw material at its command needed a professional journal having for its purpose the dissemination of knowledge of what is going on in that industry.

The welcome which *The Refiner and Natural Gasoline Manufacturer* has had even in advance of its first issue confirms our belief that the industry will welcome such a journal.

If we came to you with simply "another oil journal," we would deserve no sympathy, no support nor friendship at your hands. We would be nothing more than a leach upon the industry we claimed to serve.

But we present *The Refiner and Natural Gasoline Manufacturer* to you with no such idea. Its idea is one of service. It will bring to its readers each issue new data on refinery methods, written by professionals who are in a position to write with authority. It will bring to you information on new processes of refining oils—which it will not present as a panacea for refining ills, but simply as news to be taken for what *you* think it is worth.

We recognize that one of the greatest obstacles facing a publication of this kind is the reputation which oil publications—through no bad intention on their part—have suffered from insofar as the refinery superintendent is concerned. "Not half of what you read is true—and it seems that the writers of refinery articles are anxious to cover space and yet not release any of their own trade secrets," was the way one professional put it recently.

It is our hope that *The Refiner and Natural Gasoline Manufacturer* will become a publication for which the refinery engineer will be willing to write, knowing that the professionals who read are their fellows in every respect.

And to this end, we crave help. We know that the field exists, our friends in the industry have confirmed our belief in it, but the greatest service can only be had through the greatest cooperation from those who compose the profession to which *The Refiner and Natural Gasoline Manufacturer* earnestly dedicates itself.

R. L. Dudley
President, Gulf Publishing Company
September 1922

LEE NICHOLS, VP, Content/Editor-in-Chief

Up to the 1930s: Whales, lamps, automobiles, plastics and war

In this anthology, *Hydrocarbon Processing* will provide a detailed history of the origins and evolution of the hydrocarbon processing industry (HPI). This robust analysis will chronicle the beginnings of the modern refining and petrochemical industries through the technological advancements that have created the global energy juggernaut the industry has become today. This examination of the history of the HPI will dictate how human ingenuity has provided the products that have increased the standard of living for billions of people around the world, as well as a reflection on technological advancements over the past 170 yr.

The discovery of kerosene. Everything has a beginning. From the construction of roads, buildings and ship assembly to use in medicines and weaponry, ancient civilizations have been using oil for thousands of years. However, the modern refining industry traces its origins back nearly 170 yr, with the invention of kerosene by Canadian physician and geologist Abraham Gesner and the construction of new refining facilities to produce the high-demand product.

In the early 1840s, Gessner began experimenting with hydrocarbons, specifically bitumen from Trinidad. From these experiments, he developed a process to extract oil, which could be burned.[1] However, the bitumen product was expensive to obtain and the burning of it produced a horrendous odor. Therefore, he started experimenting with a tpye of asphalt called albertite. Gessner noticed that the oil that was extracted—the process was done by heating coal in a retort[2]—burned with a strong yellow flame with no odor. He termed the product "keroselaion" from the Greek words "wax oil." He later shortened the name to kerosene. Little did Gesner know that his discovery was soon to usurp whale oil in the burning of lamps and begin an international movement.

Whales, lamps and refineries. Through the late 1800s/early 1900s, whale oil was used extensively as a fuel for lighting. The oil, which is more of a liquid wax, was obtained from the blubber from the head of whales. The oil was processed and sold as a fuel for lamps, lubrication, making soap or to produce candles. Although highly dangerous, the whaling industry grew significantly as consumer demand for oil to fuel lighting expanded exponentially.

The whaling industry peaked in the 1820s and declined over the next several decades. Decreasing whale populations and taxation led to higher prices for whale oil, which could not compete against other options, such as kerosene. Consumers' pocketbooks dictated the pathway to the adoption of a cheaper and comparable alternative, ushering in a new era of refined products.

Several years after Gesner's discovery of kerosene, Samuel Kier began his own experimentation on petroleum that would seep into his family's salt wells near Pittsburgh, Pennsylvania (U.S.)—at the time, this substance was known as "carbon oil." Although the substance could be burned for lighting, much like Gesner's experiments with bitumen from Trinidad, the unrefined material had an unpleasant odor. Instead, Kier used the material for medicinal purposes until it lost its appeal in the early 1850s.

To find another path for the oily substance, Kier experimented with using the substance for lighting. On the recommendation of James Booth, a chemist and professor from Philadelphia, Pennsylvania (U.S.), Kier used distillation to extract the best materials for the use of lamp burning fuel. In 1851, Kier began selling his lamp fuel oil for \$1.50/gal, a more cost-effective product than whale oil.[3] As demand grew, Kier established North America's first oil refinery in 1853, which processed 1 bpd–2 bpd of liquid petroleum in its first year, growing to 5 bpd in 1854 (**FIG. 1**). In 1859, Edwin Drake drilled the first commercial oil well in North America in Titusville, Pennsylvania. After trial-and-error, he discovered oil at a depth of nearly 70 ft. Soon, his commercial well produced 25 bpd. The oil was destined to be sold to a local refiner to produce kerosene for lamp fuel. His first customer: Samuel Kier.

Nearly 4,300 mi away, Ignacy Łukasiewicz started to produce kerosene in the early- to mid-1850s, as well. After experimenting with different oils extracted by wells drilled near Bóbrka, Poland and other sites he set up with local business entities, Łukasiewicz opened Europe's first oil distillery in 1856 in Jaslo. The refinery was established to produce kerosene for lamp lighting. Shortly thereafter, a larger scale refinery was built in Ploieşti, Romania by brothers Teodor and Marin Mehedinţeanu.[4] The Râfov refinery used cylindrical iron and cast iron vessels, which were heated by wood fire, to produce 7 tpd of distilled oil.[5] The oil was ultimately used as lamp lighting fuel, leading Ploieşti to become the first city to be lighted by distilled crude oil.[5]

In the 1860s, John D. Rockefeller established and increased the size, wealth and power of Standard Oil Company, which produced and shipped kerosene, eventually becoming a monopoly within the U.S.—the company was eventually split into several entities that would lead to the creation of Amoco, Chevron,

Exxon, Mobil and Marathon. By the mid-1890s, Standard Oil Co. had also become the dominant kerosene exporter to other parts of the globe, such as Asia. However, Standard Oil Co. soon found a competitor in the kerosene trade, a European trading company called Shell Transport and Trading Co.—the company established its first refinery in Balikpapan, Indonesia in 1897 (known as Dutch Borneo at the time).[6] In 1901, Shell Transport and Trading Co. merged with a smaller competitor—Royal Dutch—that had set up a sales organization in Asia. The company took the name the Royal Dutch Shell Group. The company's operations—drilling, exploration and refining—expanded rapidly to various parts of the globe.[6]

As oil exploration began to increase globally, new refineries were being built in various locations worldwide to produce kerosene and gasoline. For example, after oil was discovered by accident in northeast India, the Assam Oil Co. opened the Digboi refinery in Digboi, Assam, India. The refinery, which produced kerosene, was the first refinery in Asia.[7]

In 1908, George Reynolds, backed by English investor William D'Arcy, discovered oil in Persia (modern-day Iran). Four years later, the Anglo-Persian Oil Co. (APOC) opened the Middle East's first refinery in Abadan, which would become the largest refinery in the world. However, APOC found it difficult to find a market for its oil, primarily due to intense competition from more established companies (e.g., Standard Oil Co.). The company soon found an ally in Britain's newest Lord of the Admiralty, Winston Churchill. Churchill was assigned to modernize Britain's navy, which included switching from coal-powered ships to using oil. Not wanting to rely solely on Standard Oil or Royal Dutch Shell, Britain signed a lucrative oil deal with APOC, which resulted in Britain becoming the majority shareholder in the company. A little over 40 yr later, the company adopted the name British Petroleum (bp).[8]

FIG. 1. Samuel Kier standing next to his 5-bpd petroleum still. Photo courtesy of the Drake Well Museum.

The genesis of synthetic plastics. In the mid-1850s, English inventor Alexander Parkes was conducting research on cellulose—an organic material component in the cell walls of green plants and the most abundant biopolymer in the world at the time. His research/tests, which included treating cellulose with nitric acid and a solvent, led to the creation of Parkesine, the world's first thermoplastic.

A few years later in 1861, English chemist Thomas Graham discovered a new substance while dissolving organic compounds in solutions. He noticed that some of the substance (e.g., cellulose) would not pass through fine filter paper, leaving behind a sticky residue. He termed this substance "colloids" after the Greek word for glue. The use of colloids led to research that would lead to the birth of new plastics technologies and commercial production.

The American inventor John Wesley Hyatt acquired Parke's patents and began experimenting with colloids and natural polymers. In 1870, he discovered celluloid—one of the world's first plastics—by applying heat and pressure to a mix of cellulose nitrate and camphor. In the late 1880s, French engineer and industrialist Count Hilaire de Chardonnet used a nitrocellulose solution to create "Chardonnet silk," which was a synthetic silk and the basis for rayon—rayon fibers are still produced and less flammable than the ones produced in the 1890s.[9]

Up until the early 1900s, plastics were produced using organic materials.

That changed in 1907 with the discovery of Bakelite by Belgian chemist Leo Baekeland. His process involved reacting phenol and formaldehyde—in the presence of a catalyst—under pressure at high temperatures, which occurred in his innovative Bakelizer—a steam pressure vessel (**FIG. 2**). The result was an extremely versatile resin that could be molded and shaped. This invention was the world's first synthetic plastic.[10] Five years later, Swiss chemist Jacques Brandenberger invented Cellophane—a transparent sheet made from cellulose, which was primarily used as a packaging material. Around the same timeframe, German chemist Friedrich Klatte patented a method for polymerization of vinyl chloride to produce polyvinyl chloride (PVC). **Note:** PVC was first discovered in the 1870s by the German chemist Eugen Baumann but never patented.[11]

A new process for fertilizer production. Using fertilizers for agricultural significantly expanded in the 1800s/early 1900s. However, the primary sources to develop ammonia—niter and guano—were not adequate to satisfy demand; therefore, a new process was needed to produce adequate amounts of ammonia and nitrates. This challenge was solved by the German chemist Fritz Haber in 1909 and later commercialized and expanded by Carl Bosch of BASF. Baden Aniline and Soda Factory (BASF) traces its roots back to 1865. The company started as a producer of dyes and inorganic chemicals, and, at the turn of the century, added ammonia production to its products portfolio.

The first industrial-scale production plant based on the Haber-Bosch process began operations at BASF's Oppau facility in Germany in 1913 (**FIG. 3**). This process—still in use today—enabled BASF to become the first company to employ high-pressure technology.[12] The process was also employed in the production of nitrates for munitions during World War I (WWI). The Oppau facility's success with ammonia production expanded to include a second site in Leuna, Germany. This site would not only utilize the Haber-Bosch process to produce ammonia but would also be instrumental in the research and development of synthetic gasoline from the hydrogenation of lignite (i.e., the Bergius process, the forerunner to the Fischer-Tropsch process). Other ammonia process pioneers (e.g., the Italian chemist Luigi Casale) would create their own technologies in later years, which would compete against the Haber-Bosch process.

The internal combustion engine (ICE). The production of kerosene included byproducts, such as straight-run naphtha, the forerunner to gasoline.[13] At the time, this product was usually discarded since there was no clear intended use for the material. However, the onset of the ICE changed the nature of oil refining, as it created an outlet for a byproduct that, at the time, had no real use.

Early pioneers of ICE designs include the French-born Swiss inventor François Issac de Rivaz, French brothers Claude and Nicéphore Niépce and English inventor Samuel Brown. De Rivaz's design—invented in 1807—used an electric spark to ignite hydrogen and oxygen.[14] Although his design led to the first ICE incorporated onto a carriage (a primitive automobile), it was never commercially successful. In the same year, the Niépce brothers patented their own ICE design. The Pyréolophore used a mixture of lycopodium powder, coal dust and resin for ignition purposes.[15] The brothers proved the concept of their design by conducting a test run of their ICE on a boat on the Saône river in France. The successful test led to the brothers receiving credit as the first to use an ICE on a boat.

Samuel Brown is also one of the earliest developers of the ICE (his engine used hydrogen as a fuel to propel a carriage up to 7 mph in 1828 and a river boat up to 6 knots in 1827). Belgian engineer Étienne Lenoir's ICE design was a single-cylinder engine that used the ignition of coal gas and air to create power that drove the pistons.[16] Although inefficient, the concept led to the creation of the Lenoir gas engine and the production of rudimentary automobiles—the engine was also used for power generation.

FIG. 2. The Bakelizer, the pressure vessel Leo Baekeland used to produce the world's first synthetic plastic. Photo courtesy of the U.S. National Museum of American History (Smithsonian Institution).

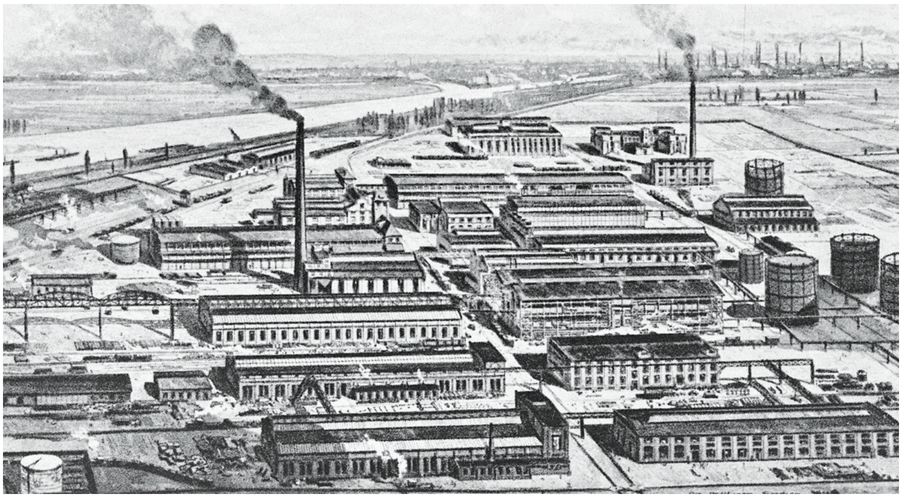

FIG. 3. View of the world's first ammonia synthesis plant. BASF opened the facility in Oppau, Germany in 1913. Photo courtesy of BASF.

Building off Lenoir's design, the German engineer Nicolaus Otto created a four-stroke piston cycle ICE in 1876. Otto's thought process was the inefficiencies in Lenoir's engine design could be solved using a liquid fuel. Gottlieb Daimler and Wilhelm Maybach—both worked at Otto's engine company in Germany in the late 1860s/early 1870s—patented their own ICE design in 1883. Their concept used ligroin (i.e., heavy naphtha) as fuel. Over the next 2 yr, Daimler and Maybach optimized their ICE design by including a carburetor that mixed gasoline with air for combustion.[17] This design led to the first installation of a liquid petroleum-fueled automobile.

Other engine pioneers improved on earlier ICE designs. For example, Rudolf Diesel designed a more efficient ICE in the early 1890s. His engine could use several types of fuels but primarily used kerosene. The concept significantly improved energy efficiency vs. other engine types, especially those run off steam or gasoline. Diesel's engine was later used in heavier industrial and transportation applications such as agricultural machinery, marine vessels, locomotives, trucks and many others.

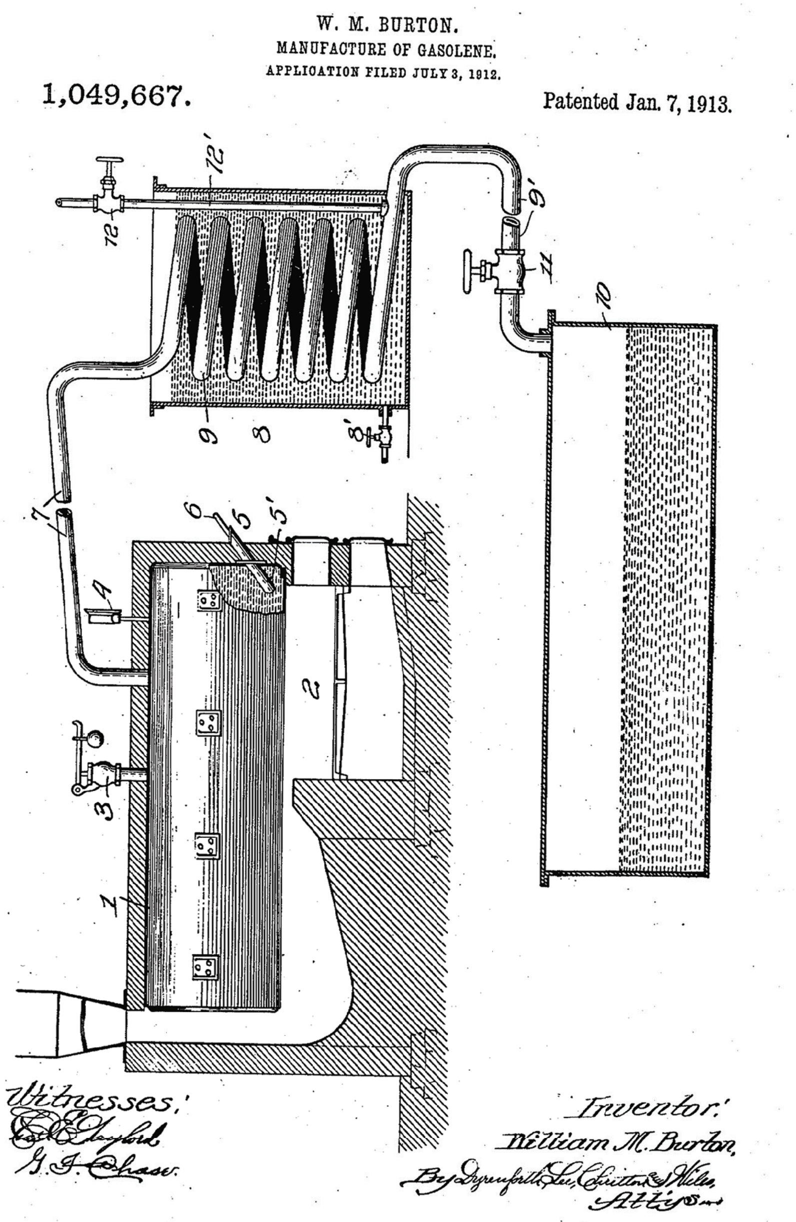

FIG. 4. View of Burton's patented apparatus for gasoline production. Photo courtesy of the U.S. Patent Office.

Thermal cracking evolves the refining process. As the production of automobiles increased, giving rise to automobile pioneers such as J. Frank, Charles Duryea, Henry Ford, William Durant, Karl Benz and several others, refined gasoline demand surpassed kerosene demand in the early 1900s. This new form of gasoline was refined, unlike previous iterations of straight-run gasoline, which was a byproduct from the kerosene production process. However, the kerosene production process used a simple distillation technique, which did not yield enough gasoline fraction to meet burgeoning demand. This challenge was solved by the invention of the thermal cracking process.

The earliest thermal cracking process was patented by Vladimir Shukhov in Russia in 1891. The Shukhov Cracking Process used high pressure to "crack" heavier hydrocarbon chains into lighter, shorter chains.[18] However, Shukhov's process found little adoption since a market for lighter fraction fuels (e.g., gasoline) did not exist at the time. It was not until the worldwide growth of automobiles did gasoline demand increase in prominence.

In 1910, Americans William Burton and Robert Humphreys developed their own thermal cracking process while working at Standard Oil of Indiana's Whiting refinery—the refinery was originally established to produce kerosene for lamps. According to literature[18], the process involved heating crude oil in a still to 371°C–399°C (700°F–750°F). The petroleum vapors were regulated through a valve system that maintained constant pressure through the entire process. Once the fractions were evaporated, they gathered through a condenser. Lastly, the still was opened and the carbon deposits were collected. The process produced primarily gasoline, gasoil, residual fuel oil and petroleum coke.[18] A view of Burton's apparatus for the process, submitted to the U.S. Patent Office in January 1913, is shown in **FIG. 4.** The process significantly expanded the Whiting refinery and led to many other refining companies licensing the thermal cracking technology from Standard Oil of Whiting. The Burton process was used extensively for more than 20 yr, until the creation of catalytic cracking. It was not until after WWI that advances to the thermal cracking process accelerated within the industry. **Note:** One of the earliest pioneers in catalytic cracking was the American Almer M.

McAfee, who created a process that used anhydrous aluminum chloride-based catalyst that produced a higher yield of gasoline from the distillation process. McAfee's employer, Gulf Refining, would launch the first anhydrous aluminum chloride cracking unit in Port Arthur, Texas in 1915.[19]

In the same year Burton was patenting his thermal cracking process, German scientist Friedrich Bergius developed a new synthetic fuel process. The direct coal liquefaction process—a predecessor to the Fischer-Tropsch process, which used an indirect method for coal liquefaction—involved reacting hydrogen at high pressures with lignite to produce liquid fuels.[20]

National defense: War ushers in a new era for oil. Prior to the start of WWI, coal was the dominant source of fuel for marine vessels, especially for navies. However, the benefits of using oil soon became prevalent around the world. The fuel had double the energy intensity of coal, refueling at sea was easier, it enabled better flexibility in changing speeds, fewer crew members were needed to operate a ship's fueling system and oil produced less smoke than coal—an imperative for line of sight when aiming cannons at enemy vessels.[21]

In 1914, WWI began in Europe. The 4-yr conflict significantly expanded the use and demand for oil. The war effort included the use of tens of thousands of trucks, motorcars and motorcycles, hundreds of ships and the introduction of airplanes and tanks, all using ICEs that ran off gasoline and used oil for lubrication. The use of oil became a mainstay for transportation, which continued after the war.

Demand increases and technologies advance. As WWI ended, global gasoline demand expanded immensely. Although thermally-cracked gasoline was the dominant choice in ICEs, premature combustion caused knocking, which can cause several problems with an engine's operation. New research efforts were devoted to find solutions to this challenge. This included optimizing the thermal cracking process. C. P. Dubbs created a modified thermal cracking process (i.e., the Dubbs process) that operated at 400°C–460°C (750°F–860°F), which lessened carbon buildup in the system, enabling the process to operate longer before cleanout. Dubbs licensed his process for nearly two decades under the company name National Hydrocarbon Co., later changing the name to Universal Oil Products (UOP).[22]

In 1921, while working at General Motors, Thomas Midgley—who later also helped invent Freon—discovered that incorporating tetraethyllead (TEL) into gasoline prevented knocking in ICEs (increasing gasoline octane rating leads to better compression and, in turn, improved engine performance). Around the same timeframe, chemists at Standard Oil Co. of New Jersey produced isopropyl alcohol (IPA), which is credited as the first commercial petrochemical—it was a synthetic alcohol. Just one year later (September 1922), the inaugural issue of *The Refiner and Natural Gasoline Manufacturer* was published to provide technical articles and know-how to the global refining industry (later including petrochemicals and gas processing/LNG technical materials, as those industries evolved). The publication would change its name several times—evolving with discoveries in new industrial processes—before taking the name *Hydrocarbon Processing.*

Several other technological advances in refining and petrochemicals production happened in the 1920s. These included the discovery of synthetic rubber (styrene-butadiene rubber or SBR) by the German chemist Walter Bock, synthetic methanol by the German chemist Matthias Pier, the production of moisture-proof cellophane, the Fischer-Tropsch process for liquids production (coal liquefaction and gas-to-liquids), the discovery of silicones, an improved method to produce PVC by the American inventor Waldo Semon, the first ethylene plant built by Union Carbide in West Virginia (U.S.), and early research by French inventor Eugene Houdry that would eventually lead to the development of the catalytic cracking process in the 1930s.[23] These milestones in the refining and petrochemicals industries helped provide the foundation for the acceleration of the industry to develop new and better products for the global population.

The 1930s. Over the following decade, the global HPI continued to evolve and advance technologies for fuels and petrochemicals production. The industry's milestones of the 1930s included the discovery of catalytic cracking, polyethylene and synthetic resins. HP

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LEE NICHOLS, VP, Content/Editor-in-Chief

Advancing processing technologies and refining operations: Excerpts from the 1920s

The following is a mixture of technical articles, columns and headlines published in the 1920s by *The Refiner and Natural Gasoline Manufacturer*, the forerunner to *Hydrocarbon Processing*. This collection of excerpts provides a look into the major technological advancements and topics/trends in the hydrocarbon processing industry during that timeframe.

Comparison of principles involved in existing cracking processes

L. Reiss and E. R. Lederer, January 1923

This article detailed the nine different classifications under which cracking processes fall:

1. Cracking in stills under pressure
2. Cracking in the liquid phase in tubes under pressure
3. Cracking in the liquid-vapor phase in tubes under pressure
4. Cracking by any of the above, using steam
5. Cracking by any of the above, using fixed gases and hydrogen
6. Cracking by any of the above, using chemicals
7. Cracking with the aid of internal heat
8. Cracking in the vapor phases in tubes under pressure
9. Cracking by electrical methods.

Some advantages of Dubbs Cracking Process

E. R. Lederer and W. F. Fulton, February 1923

The authors detailed the advantages of the Dubbs Cracking Process. Most notably, the Dubbs plant has the advantage of being able to handle up to 20 t of carbon or coke, which is deposited out of the heating zone in the expansion chamber where it can be easily removed at the end of the run without any material injury to the apparatus, thus permitting continuous operation over a longer period than any of the other methods in commercial use at the present time.

High recovery claim of Cross process

R. Cross, March 1923

During the early 1920s, many companies were conducting research to increase gasoline yield in refining. The author wrote, "Never in the history of the petroleum industry has there been so much activity in methods of increasing the yield of gasoline from crude oil. During the last 12 mos, most important advances in practical cracking have been made." This article provided details on a new process, which essentially is a process of producing synthetic crude that is subsequently distilled.

Blending distillates and gas condensates

G. W. Reid, April 1923

This article provided new insights on the blending of petroleum distillates and natural gas condensates. The primary purposes of the author's experiments were to detail physical changes that occurred when blending is in process and distillates and condensates are being mixed. Are the changes purely physical, purely chemical or a mixture of both?

Copper dish and "doctor" tests not so good

J. V. Meigs and E. J. Ford, May 1923

The authors provided insights on how the present way of determining corrosive elements in gasoline could be greatly improved, as well as offering their opinion on better methods.

Editorial Comment: Can there be too many cracking plants?

R. L. Dudley, June 1923

What will be the result if most refineries install cracking plants? Won't this mean an over-production of gasoline with resultant lower prices? These questions were answered within a survey conducted by the publication in 1923. The majority response was, "yes, more cracking processes probably will lower the cost of gasoline if the present supply of crude continues, but economically and financially the cracking process will be vindicated more as the years go by."

Cooling condensing water a problem

H. Pennington, April 1924

The value of cool condensing water is felt by every refiner running light oils, especially during summer months when atmospheric temperatures run high, and condensers are apt to "blow." This challenge is not always given much attention but has a prominent place in operating efficiency.

Comparing gasoline plant operating costs

D. E. Foster, April 1924

The big problem of a gasoline plant is not simply running the plant and making gasoline, it is making money on the invested capital. This article detailed the economics of three methods of producing natural gasoline in 1924: compression, compression-blending and oil absorption.

Power costs reduced by electric drive

H. Pennington, August 1924

This discussion covered the application of steam turbine-driven generators for refinery operations in such a way that the steam is given superheat in the boilers, put through the turbine, where power is skimmed from it, and the steam is reduced in pressure, then passed out into the header, supplying stills with naked steam for distillation purposes.

Refining without shutdown for rerun

G. W. Reid, September 1924

From a study of approximately 40 refining plants, it is evident that progress is being made toward the accomplishment of taking care of rerun distillates without shutting down the plant during crude oil runs. Circulating distillates through towers prevents the accumulation of stocks and increases recovery.

Gasoline being extracted from shale

October 1924

M. J. Trumble has perfected a process for extracting oil and gasoline from shale in an experimental plant located at Alhambra, California (U.S.). The process is cyclic in character; that is, instead of producing the oil from shale in one operation and then distilling the crude oil into gasoline and other products in a second operation, the gasoline is produced from the oil shale through one continuous operation in which the crude oil occupies only an intermediate stage.

Boiler efficiency essential to refining

H. Pennington, November 1924

Temperature regulation for towers

W. C. Begeebing, November 1924

It has only been in the last few years that efficient fractionating towers and reflex condensers have come into general use. Tower construction has been greatly improved and with it has come the widespread adoption of automatic temperature control.

Many methods used in treating operation

C. K. Francis, March 1925

As the demand for higher quality product increases, more knowledge of various systems is being sought. This paper reviewed new methods to increase product purity from the refining process.

Review, comparison of fractionating towers

W. A. Peters, March 1925

This article detailed how the flexibility of a bubble tower can produce the desired product in only one run.

Essentials of plant lubrication

C. A. Fitz-Gerrell, May 1925

The correct type of oil is one that supplies fluidity in the delivery of the maximum of power in an even, steady flow through the stress of all operating conditions. Vital points to consider are maximum load and operating temperatures.

Accounting system for a refinery with a cracking system

R. J. Omo, July 1925

It was found that a cost system was necessary in operating a plant. The system that is described in this article provides the plant superintendent the cost of each step in the manufacturing process, and whether that person was overstepping a predetermined economic limit, and if so, why.

Fuel oil—Its uses and methods of analysis

August 1925

The use of oil fuel is now becoming general in all trades and industries, the majority of which, were up until a few years ago, entirely dependent on coal. This article detailed the uses of fuel oil—especially in marine travel—and comparing various specifications.

Oil a source of raw material for chemical industries

J. E. Meyer, October 1925

Prevention of evaporation losses from gasoline storage

R. E. Wilson, H. V. Atwell, E. P. Brown and G. W. Chenicek, October 1925

The loss of gasoline from storage tanks with roofs tight enough to keep out the wind is due almost entirely to the daily breathing out of gasoline-saturated air as the temperature increases.

The future of gasoline

E. J. Ford, December 1925

This outlook provided insights on the next decade of gasoline demand (up to the mid-1930s). The author believed gasoline demand would continue to increase due to the rise in automobile demand—a more convenient way of travel vs. railway—and the increase in air travel. "Probably even more likely is the possibility of larger planes or small dirigibles for interurban transportation. No one will deny that the day of long-distance air travel is fast approaching."

Decreasing refinery evaporation losses of gasoline

L. Schmidt, March 1926

In 1925, gasoline losses through evaporation totaled approximately 6.3%. However, better equipment and process changes have cut that loss in half. The improvement on various vapor-saving equipment and knowledge will further reduce gasoline losses from evaporation.

Contributing factors to corrosion, with special reference to sulfur

C. K. Francis, March 1926

Sulfur can wreak havoc on a refinery's operation. No matter how the sulfur was formed in feedstock material, methods must be studied and devised to control and get rid of it.

Proper design and operation of heat exchangers

F. L. Kallum, M. E. Semino and A. F. Semino, April 1926

Production of heat is the costliest item in petroleum heating. Once produced, the conservation of heat offers opportunity for perhaps the greatest saving in the operation of a refinery or natural gasoline plant. This is the primary reason for the development of the heat exchanger in refining circles in the last 5 yr.

How to conserve steam in a refinery

H. S. Bell, May 1926

No matter how efficient a refiner's boiler house may be, they must use the steam intelligently and without waste to reap full op-

erational benefits. This article provides detailed analysis on the wastes that are often encountered in the steam distribution system and offers suggestions for conserving steam in the refinery.

Cracking heavy hydrocarbons in the presence of catalyst

I. Ginsberg, November 1926

Our article is concerned with a discussion of certain results that were obtained in the cracking of heavy hydrocarbons, mineral oils, mineral oil residues, ozocerite and the like into lower boiling products by heating them to the boiling point in the presence of activated charcoal and other catalysts.

Corrosion—An economical refinery problem

H. F. Perkins, January 1927

Only within the last few years have we been informed of the real mechanism of corrosion, and we are now ready to study each case of corrosion individually based on this information and depart from empirical methods.

Centrifugal vs. reciprocating pumps for refinery service

W. R. Layne, March 1927

This work provides a detailed comparison of two pump types: centrifugal and reciprocating. The best economy will be considered that results in the lowest total cost of pumping per barrel.

Refining capacity shifting to integrated companies

G. Reid, June 1927

The use of solvents for dewaxing paraffin-base crude oil

H. M. Smith, October 1927

A method utilizing solvents for the purpose of separating and removing waxy material is described in this article, together with preliminary experiments with solvents that led to its development. The solvents used are secondary butyl alcohol, acetone and mixtures of these, as well as isopropyl alcohol.

Using chemicals protects distillation equipment against corrosion

G. Egloff and J. C. Morrell, December 1927

The economic losses due to corrosion are high. This article considers the injection of chemicals into refinery equipment to neutralize the corrosive substances resulting from the atmospheric and super atmospheric distillation of petroleum oils.

Clays and their application in refining

G. W. Cupit, April 1928

The various benefits of using clays in petroleum refining are discussed in this article.

Automatic control equipment in the modern refinery

C. B. Faught and F. R. Staley, May 1928

A surprisingly large percentage of the total operations in a modern refinery are still classed as manual. However, increasing automatic control on equipment can optimize refinery throughput and efficiency.

Methods of testing gasoline for anti-knock properties

July 1928

This table, provided by H. G. Koehler of the Research Laboratories of the Universal Oil Products Co., provide data relative to the various methods of testing gasoline for anti-knock properties.

The plant manager's part in accident prevention

C. W. Price, August 1928

There are three qualifications that are indispensable to a manager who would successfully promote safety at the plant. The plant manager must:

1. Believe in safety as a good business proposition
2. Believe in safety wholeheartedly and express those same principles to the plant workforce
3. Not only initiate a safety campaign but must continuously associate with safety activities.

Natural gasoline outlook brighter: Expansion in cracking facilities indicates large demand and improved market for 1929

H. J. Struth, February 1929

Gasoline plant gathering system design

J. C. Bolinger, April 1929

In the design of pipelines for the transmission of gas, it is necessary to make use of some formula expressing the relations to each other of the quantity, initial and final pressures, diameter and length of line.

Special precautions for handling sulfur crudes at refineries

D. G. Cooper, May 1929

In handling sulfur crudes, hazards to personal safety and severe corrosion of equipment are encountered. Since these hazards exist in nearly all phases of the handling of crudes the utmost care in procedure must be followed.

Is present gasoline storage capacity adequate to best serve the industry?

H. C. Charles, June 1929

Few big companies dominate refinery capacity

G. Reid, July 1929

Nineteen companies control 75% of the total crude capacity and 80% of cracking facilities in the U.S.

The manufacture of commercial anhydrous aluminum chloride

A. M. McAfee, August 1929

For the first time, in this article, are the details of the aluminum chloride process made public.

Natural gasoline industry expansion slowing down

November 1929

LEE NICHOLS, VP, Content/Editor-in-Chief

The 1930s: Catalytic cracking, polyethylene, synthetic fibers, resins and jet engines

The hydrocarbon processing industry (HPI) has a rich history of discovery, challenges, breakthroughs, trial and error, collaboration and success. *Hydrocarbon Processing* continues its reflection on the history of the HPI. In the last installment, a detailed analysis was provided on the origins of the modern refining and petrochemicals industries. This included the discovery of kerosene, the construction of new refineries around the world, the production of the first synthetic plastics, the rise of the internal combustion engine (ICE), oil demand's exponential growth during and after World War I (WWI) and how thermal cracking evolved refining processing. The following will detail how the HPI continued to evolve during the 1930s.

The discovery of catalytic cracking. After serving in WWI in the French artillery division and later in the tank corps, French engineer Eugene Houdry worked in his father's steel business. Outside of work, Houdry had an interesting hobby, racing cars. Through these endeavors, he began to develop a passion for improving engine performance.

With the significant increase in gasoline demand after WWI, many forecasters feared that thermal cracking was unable to satisfy future global demand. Like many other researchers around the world, Houdry was trying to develop a new way to develop high-performance fuels.

In the late 1920s, he and French scientist E. A. Prudhomme developed a three-step process to convert lignite to gasoline. However, a major problem with the process was that the catalysts would get coated with carbon, lessening their effectiveness. To solve this challenge, Houdry used Fuller's earth (a naturally occurring aluminosilicate), which effectively produced gasoline from lignite.[24] However, pilot plant demonstrations yielded less than expected results and the process was deemed uneconomical.

Unable to secure additional financial backing, Houdry moved to the U.S. and eventually started working with Socony-Vacuum and Sun Oil Co. to perfect his process. In 1936, the first Houdry Unit began commercial operations at Sun Oil's Marcus Hook refinery in Pennsylvania—it was the first fixed-bed catalytic cracking unit.[23] Approximately 50% of the 15,000-bpd unit produced high-octane gasoline, which was double the production of conventional thermal processes.[24] Around the same timeframe (circa 1938), the alkylation process was commercialized in the U.S. The process produced high-octane aviation gasoline, which saw significant demand increase during World War 2 (WW2). The process was then used in the 1950s to produce blending components for automotive fuel.

The catalytic cracking process was later improved upon by Warren Lewis and Edwin Gilliland while working for Standard Oil of New Jersey (U.S.). According to literature,[25] the improved process included a continuously circulating fluidized catalyst made of fine zeolite powder. Houdry's fixed-bed unit gave rise to research and development by other companies that led to the invention of the fluid catalytic cracking process in the 1940s.

Coking and gasification evolve. The first delayed coker was built in 1929 by Standard Oil of Indiana (the company would later become bp). The Burton thermal cracking process produced coke that would be sent to a vertical coke drum. However, cleaning the vertical coke drum required arduous manual labor. It was not until the late 1930s that Shell introduced hydraulic decoking at its refinery in Wood River, Illinois (U.S.), which used high-pressure water to clean coke drums. This process enabled refineries to use two coke drums for continuous operation.[26] Over the next several decades, coking would become a staple in refining operations.

In the mid-1930s, Lurgi GmbH (now a part of Air Liquide) invented a novel coal gasification process. The pressurized, dry-ash, fixed-bed gasifier would use coal to produce synthesis gas (syngas). The first commercial Lurgi dry-ash gasification plant started operations in 1936, and the process is still in use today.

Polyethylene: An accidental discovery. In 1933, while working at Imperial Chemical Industries (ICI) in Northwich, England, Eric Fawcett and Reginald Gibson stumbled upon a white, waxy substance during experiments they were conducting on ethylene and benzaldehyde. The experiments included heating the mixture to 170°C at an extremely high pressure—more than 1,900 bar—in an autoclave. However, the reaction was a safety hazard due to the explosive nature and research was halted.

Two years later, ICI scientists Michael Perrin, John Paton and Edmond Williams began to conduct additional research on Fawcett and Gibson's discovery. In this iteration, the scientists repeated Fawcett and Gibson's test but focused solely on ethylene. What the three did not know was that the pressure vessel used leaked, leading to a loss of pressure. Once the reaction was completed, the trio noticed a white powdery substance remained—one lab technician described the substance looked like a lump of sugar.[27] The scientists had accidentally stumbled upon polyethylene (PE), which would revolutionize society.

Over the next several years, ICI perfected the process and found practical uses for the material (the first item ever made with PE was a walking stick[28]) that would not only produce products to modernize society but also aide the Allies in WW2.

ICI produced the first ton of PE in 1938 (FIG. 1). In 1939, the first commercial-scale PE plant went into operation. The 100,000-tpy plant was instrumental in producing PE on an industrial scale. Within the next few years, many PE plants went into operation, primarily to aide in the allied war effort. PE was used extensively as insulating material for radar cables during WW2. The material was lightweight, which enabled Britain to install radar in their fighter planes, providing a significant technical advantage in long-distance air warfare.[27,28] Due to this wartime advantage, the production of PE for insulated cabling was highly-secretive. It was not until post WW2 that the production of PE was commercialized. Within several years, PE production capacity significantly increased and would later become the world's most used thermoplastic.

FIG. 1. A commemorative sample of the first ton of PE produced by ICI in 1938. The initials G. F. are that of George Feachem, a chemist that was on duty the night PE was produced in laboratory tests in 1933. According to family members, Mr. Feachem kept this token in his wallet until his death. Photo courtesy of BBC History of the World.

FIG. 2. Carothers demonstrates the elasticity of neoprene. Photo courtesy of the Science History Institute.

New chemical discoveries with lasting legacies.

Several new chemical discoveries took place in the 1930s that have provided the global population with new products to improve standards of living. These included the discovery and production of polystyrene, polyepoxide, nylon, polyester and neoprene.

Polystyrene. Although discovered in the late 1830s, styrene—which would lead to the production of polystyrene—would not be commercialized for nearly 100 yr. In 1839, German chemist/pharmacist (referred to as an apothecary) Eduard Simon distilled an oily substance from storax, a resin from a sweetgum tree. He noticed several days later that the material—which he called styrol—thickened into a jelly-like substance. Thinking the reaction was due to oxidation, Simon termed the substance styrol oxide.[29] However, it was not until 80 yr later that a practical use was found for the material.

In the 1920s, research/writings by German chemist Hermann Staudinger led to the invention of polystyrene. Staudinger demonstrated that thermally processing styrol produces macromolecules, which he characterized as polymers. His technical research/writings would eventually lead Staudinger to be awarded the Nobel Prize for Chemistry in 1953.

Commercialization of styrene polymers began in the early- to mid-1930s by IG Farben in Germany and Dow Chemical in the U.S.—styrene production increased significantly in both Germany and in the U.S. during WW2 to produce synthetic rubbers to aide in the war effort. In the late 1930s, Dow Chemical engineer Ray McIntire was experimenting with a polystyrene process developed by Swedish inventor Carl Munters. By accident, McIntire created foam polystyrene which expanded approximately 40 times in size.[30] Dow would later commercialize this discovery as expanded polystyrene, better known and marketed under the name Styrofoam.

Neoprene and nylon. While focusing on research conducted by Staudinger and Belgian-born priest and chemistry professor Julius Nieuwland, Wallace Carothers' polymers research group at DuPont discovered two major chemical applications: neoprene and nylon. While a professor of chemistry at the University of Notre Dame (U.S.), Nieuwland focused his research on acetylene chemistry, which led to the discovery of divinyl acetylene—a jelly-like substance that hardens into an elastic compound similar to rubber.[31] DuPont purchased the patent rights to this new discovery, and Nieuwland joined Carothers' research team to conduct further research and testing on practical applications for this and other polymer applications. One of Carothers' colleagues, Arnold Collins, discovered neoprene while conducting further research on divinyl acetylene. Through several testing methods, Collins soon discovered a mixture that produced a clear homogeneous mass that bounced. The product—chloroprene—was used to produce the polymer polychloroprene, which later became the new synthetic rubber neoprene.

Neoprene was first marketed in 1931 under the name DuPrene; however, the product was re-envisioned since it contained an odor due to the manufacturing process. By the mid- to late-1930s, the improved product—suitable for many applications (construction, automotive, medical equipment, fabrics, electrical equipment, textiles, among others) and marketed under the generic name neoprene—generated substantial revenues for DuPont.

After the discovery of neoprene, Carothers' team turned their sights on producing synthetic fibers. By the mid-1930s, Carothers produced fibers comprised of amine, hexamethylene diamine and adipic acid. However, water produced during the condensation reaction process would fall back into the mixture, preventing the creation of more polymers. After adjusting the process, Carothers pro-

duced strong, elastic fibers.[32] The new material was called polymer 6,6 (or nylon 66) since the two monomers that comprise the substance each contained six carbon atoms (**FIG. 2**). Nylon first became a household product as women's hosiery, later being used in the U.S. war effort to produce parachutes and tents. Over the next several decades, nylon would be used extensively as a combined fabric in fashion and apparel, as well as in several industrial applications—the global nylon industry market size is forecast to reach more than $46 B by the late 2020s.[33]

Polyester. Carothers' research also led to the discovery of polyester in the early 1930s. However, the discovery of nylon pushed additional research on polyester to the backburner. It was not until the late 1930s that British scientists John Winfield and James Dickson expanded on Carothers' work on synthetic fibers. Their research would eventually lead to the development of polyethylene terephthalate (PET) in 1941, which they marketed under the name Terylene. DuPont would later purchase the rights of the British scientists' discovery and develop a new synthetic fiber in the mid-1940s they called Dacron. In the early 1970s, PET began to be used in the production of plastic bottles, and today, PET is the fourth most produced polymer after PE, polypropylene and polyvinyl chloride.

Resins, epoxies, polyurethane and Plexiglas. The DuPont company was not finished with major polymer discoveries of the 1930s. In 1938, Roy Plunkett was assigned to research chlorofluorocarbon refrigerants to find a better way to refrigerate food. Much like the discovery of PE, an accident led to the discovery of another important product still in use today. Plunkett stored 100 lb of tetrafluoroethylene gas in small cylinders at dry-ice temperatures [approximately –78°C (–109°F)] before chlorinating it. When he opened the cylinder, instead of gas pouring out, Plunkett noticed a white powder had formed (**FIG. 3**).[34] Further investigation found the substance to be heat resistant and had a low surface friction. DuPont polymer scientists determined that the tetrafluoroethylene gas polymerized to produce the material, which DuPont would later market under the name Teflon.

In 1936, while working at Monsanto Chemical Co., William Talbot produced melamine formaldehyde by polymerizing formaldehyde with melamine. This new substance was a thermosetting plastic that was very good at maintaining strength and shape. Melamine resins were used for many different applications, including in utensils, plates, furniture, cups, bowls, laminates, toilet seats, automotive and epoxy coatings, among others.[35]

Within the next 3 yr, other significant chemical discoveries were made. In 1936, British chemists John Crawford and Rowland Hill discovered polymethyl methacrylate (PMMA) while working at ICI in England. PMMA is a clear thermoplastic resin that is more transparent than glass and 6x–7x more resistant to breakage than glass.[36]

Around the same time, German chemist Otto Röhm conducted experiments with methyl methacrylate (MMA). One experiment involved polymerizing MMA between two layers of glass in a water quench. The result was a clear plastic sheet that was lighter than glass but much less prone to shatter. Röhm's chemical company—Röhm and Hass AG—soon marketed the material under the name Plexiglas (**FIG. 4**). According to literature, the first major applications of the new plastic were for aircraft windows and bubble canopies for gun turrets during WW2.[37] After this discovery, several companies around the world developed their own PMMA products under various proprietary names. Röhm and Hass AG's business lines were eventually acquired by different multinational businesses, including Dow Chemical, Arkema and Evonik.

In 1936, while working with synthetic resins to produce dental prosthesis, Swiss chemist Pierre Castan developed a solid by reacting bisphenol A with epichlorohydrin and curing it with phthalic anhydride. Castan's invention—epoxy resin—was first used for dental fixtures and casings,[38] later being licensed by Ciba Ltd., which would become one of the largest epoxy resin producers in the world.

FIG. 3. Plunkett (far right) and colleagues reenacted the discovery of Teflon in 1938. Photo courtesy of the Hagley Museum and Library.

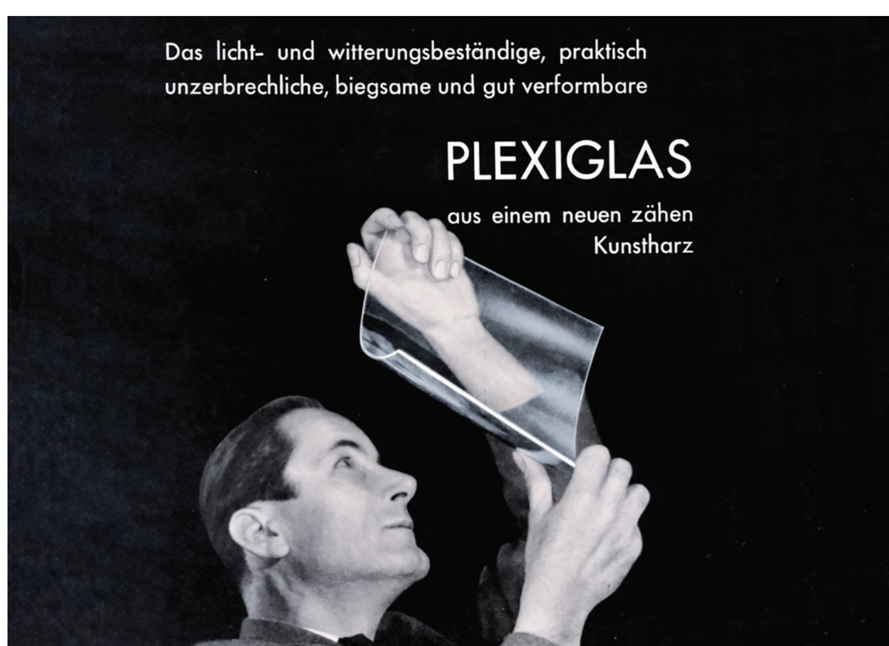

FIG. 4. After discovering Plexiglas, Röhm and Hass AG marketed the material by saying, "The light and weather-resistant, practically unbreakable, flexible and easily formable Plexiglas is made from a new, viscous synthetic resin." Photo courtesy of Evonik Industries.

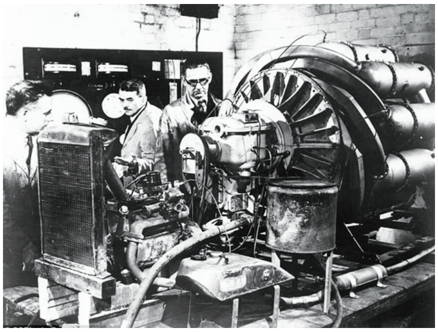

FIG. 5. Whittle and his colleagues work on the first jet engine. Photo courtesy of Getty Images.

Around the same timeframe, Sylvan Greenlee was conducting his own research on epoxy polymers in the U.S. by reacting epichlorohydrin with bisphenol A. His research created the epoxy resin bisphenol A diglycidyl ether (DGEBA or commonly abbreviated as BADGE), which would become the most widely used commercial-grade resin in the world. Epoxy resins are presently used in many industrial and commercial applications, including paints and coatings, adhesives, electrical systems and electronics, marine and aerospace applications, and many more.

While epoxy resins research and development were being implemented in Switzerland and the U.S., German chemist Otto Bayer was setting his sights on polymer research at IG Farben in Leverkusen, Germany. In 1937, Bayer created a new polymer by reacting 1,8 octane diisocyanate with 1,4 butanediol.[39] This new material was named polyurethane, which would later be used in many applications, including in construction, furniture, insulation, coatings, adhesives, sealants, elastomers, moldings, appliances, automotive, apparel and many more.

Ingenuity takes to the skies. Prior to designing engines, British engineer and inventor Frank Whittle was an airplane apprentice and pilot at the Royal Air Force (RAF) College Cranwell. Although garnering the reputation as a low-flying daredevil and aerobatics stuntman (not in a positive light), Whittle had an eye for airplane engine designs. In his graduation thesis *Future Developments in Aircraft Design,* Whittle believed that the evolution in flight would not be better propeller designs but the use of improved combustion engines for propulsion. In addition, he believed that airplanes would be able to fly faster (more than 500 mph) and farther at higher altitudes due to low air density.[40,41] However, when Whittle provided his concepts to the RAF, they were rejected as impracticable. Despite being rejected by his superiors, Whittle continued to publicize his jet engine concept and filed a patent for his engine design two years later in 1930. According to literature, the concept was a two-stage axial compressor feeding a single-sided centrifugal compressor, what he referred to as a "turbojet."[42] Whittle continued to work on building his jet engine designs over the next several years, forming Power Jets Ltd. in 1936 (**FIG. 5**).

Unbeknownst to Whittle, German physicist and engineer Hans von Ohain was developing a similar jet engine in Germany. Ohain joined aircraft industrialist Ernst Heinkel to design the Heinkel-Strahltriebwerk 1 (HeS 1) engine—German for Jet Engine 1. The first tests of HeS 1 were conducted in 1937. Although the tests were successful, the high-temperature burn—the engine ran off hydrogen fuel—scorched the metal, leading Heinkel and Ohain to switch to gasoline as fuel. Several changes were made to the design, and on August 27, 1939, test pilot Erich Warsitz flew a plane equipped with a HeS 3b centrifugal-flow turbojet engine—the latest iteration.[43] This historic day marked the world's first jet-powered aircraft flight.

Although Ohain beat Whittle to the first jet engine test flight, Whittle continued to improve his designs. As WW2 started, he received additional financial backing from the UK Air Ministry. In 1940, the first British jet-powered plane—the Gloster E.28/39—was flown using Whittle's W1A engine.[44] As war raged in Europe, the UK Air Ministry was ordering several thousand jet engines per month. By 1944, Whittle's engine design—produced by Rolls Royce—was used in the first British fighter planes, the Gloster Meteor, that could reach speeds of 600 mph.[45]

Over the next several years, jet engine designs continued to be optimized, primarily for military aircraft. However, on July 27, 1949, the world's first jet-propelled airliner made its test flight in England.[46] This historic occasion marked the first use of a jet-powered passenger plane, which would revolutionize travel. Over the next several decades, the jet-powered passenger plane would enable passengers to travel faster and farther in a shorter duration and build a nearly $200-B industry to carry billions of people each year to various destinations around the world.

The 1940s. As the world engages in conflict, demand for gasoline and chemical products soar to aid in the war effort. Post-WW2 will usher in new technological advances for producing higher octane fuels and chemical products that will increase the standard of living for hundreds of millions around the world. HP

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LEE NICHOLS, VP, Content/Editor-in-Chief

Operations, processes and safety evolve and advance: Excerpts from the 1930s

The following is a mixture of technical articles, columns and headlines published in the 1930s by *The Refiner and Natural Gasoline Manufacturer,* the forerunner to *Hydrocarbon Processing.* This collection of excerpts provides a look into the major technological advancements and topics/trends in the hydrocarbon processing industry during that timeframe.

API Division of Refining

January 1930

Through the realignment of American Petroleum Institute (API) activities to embrace three major departments (Production, Refining and Marketing), the organization has created the Division of Refining. This step is essential to improve operating efficiency and optimize the art of refining. How well the industry progresses collectively is governed by the willingness to contribute collectively.

The Division of Refining includes periodic regional conferences or conventions where tentative solutions of problems peculiar to a given refining district or, to the industry, may be discussed by refinery personnel in the various regions throughout any given year and may be the basis of highly interesting and instructive papers for presentation at group sessions at the annual API meeting.

Petroleum coke and its utilization

M. E. Schulz, January 1930

In some cracking plants, particularly those in which the heavier fractions of the crude are processed, a considerable amount of petroleum coke is formed. A refinery cracking several thousand barrels of oil per day may soon find itself with a large supply of coke on hand. What can you do with this product? We conducted some experimental work and found that coke could be used as a pulverized fuel. It is quite probable that this means of utilization will develop an important market for a large percentage of petroleum coke in some of the favorable localities. In the future, it is possible that this product will be converted from a material difficult to dispose of to a valuable byproduct of the oil refinery business.

Factors affecting the determination of gum in gasoline

C. R. Wagner and J. Hyman, January 1930

One of the more important problems that confronts the producers of cracked gasolines is that of gum formation. Such gasolines, if improperly refined, or if allowed to stand for long periods in contact with the atmosphere, seriously affect the operation of certain types of gasoline motors. Upon investigation, these motors show intake valves stuck tightly and the guides clogged with a black, brittle, carbonized deposit—referred to as the "gumming" effect of gasoline. The authors have been led to present the results of their work in the hope that they may be able to assist somewhat in clearing up the existing confusion among oil testing laboratories on this subject.

Survey shows need for curtailment of refinery runs

H. J. Struth, January 1930

A preliminary survey shows that refinery runs must be maintained at a rate not to exceed those of 1929. Forecasts show that global gasoline demand will increase 7.7% to 472 MMbbls (nearly 1.3 MMbpd).

Welding plays important part in refinery maintenance

January 1930

In present refining practice, pipe stills are replacing the older shell stills and the bubble tower or fractionating column has been adapted from the chemical industries to give clean cut separation of fractions in a single distillation. All this means that refinery equipment has suddenly become more complicated. Due to this trend, fabrication of intricate equipment is done right at the refinery, and welding has been of incalculable assistance.

Vacuum units lower costs and improve products

G. Reid, February 1930

Fire prevention and protection in oil refineries

F. L. Newcomb, February 1930

Fire prevention in oil refineries has four essentials, which are:

1. Design, which includes a clear conception of the use or occupancy of the property to obtain a safe layout with provision for future expansion, adequate strength for all structures and equipment, and the proper specification of suitable materials
2. Maintenance of structures and equipment, including systematic inspection to see that they are in a safe and fit condition for the service for which they are used
3. Care in all operations where flammable materials are handled
4. Good housekeeping or the maintenance of the entire plant in a neat, clean and orderly condition.

Securing maximum recovery from absorption

I. N. Beall, March 1930

This article is the first in a series written by Mr. Beall in the early 1930s focused on the practical application of technology to the manufacturer of natural gasoline. In discussing the problems confronting the manufacture of natural gasoline, he stated that he would like to discuss his several topics with the viewpoint that, "Theory is no better than its practical application proves it to be, and that theory without practice is as bad as practice without theory."

They are not accidents—They are self-imposed injuries

O. Peters, March 1930

Analysis of statistics leads to the conclusion that accidents are in fact self-imposed injuries. Records show that the first steps taken were in the provision of safe working conditions by the adoption of safety devices; then came the development of intelligent supervision; and now we are in the period of educating workers by teaching them the cause, the effect, the prevention and the responsibility of accidents.

Cutting losses by efficient vapor recovery

H. R. Linhoff, May 1930

Vapor recovery applies to the recovery and utilization of production, refinery and tank farm vapors, which if not recovered would otherwise be wasted. In the past, producers and refiners have been inclined to neglect the importance of vapor loss. These losses can be reduced in several ways (e.g. insulation, seals and floating roofs), but they cannot be eliminated without some system of collecting and recovering the vapors.

Operation of meters in natural gasoline plants

E. E. Stovall, May 1930

There are two methods of measuring gas that are used: the positive or displacement meter and the orifice meter measurement. This article focuses on reading the different types of meters, how to install them and computing measurements.

Progress in vapor phase cracking

C. R. Wagner, June 1930

The development of the high-compression gasoline engine has made it necessary for the refiner to market a fuel satisfactory for use in such engines. This trend has led to the commercial development of phase cracking in which the refiner is able to produce a highly anti-knock fuel from either topped crude or gasoil at a cost not out of line with the cost of gasoline made by liquid phase cracking processes.

Some theoretical considerations for the design of separators

F. L. Kallam and L. J. Coulthurst, July 1930

No two plants have the same separator design. It is self-evident that where practice is, so diversified theory is not understood. This fact has led to the present work of the subject of separators, with the hope that knowledge gained in other industries can be profitably employed toward correcting the separator failures in our own industry.

Methods of utilizing petroleum residuals and by-products

A. E. Dunstan, July 1930

In discussions on the utilization of various petroleum residuals and byproducts for power purposes, the author focuses on important topics of acid sludge, petroleum coke, asphalt residues and waste gases. His work reviews various research, experiments and results obtained in the application of these products as fuels. Part 1 of this discussion focuses on acid sludge, while Part 2 covers the usage of petroleum coke, asphalt residues and waste gases.

Lime distributing plant to combat corrosion

R. J. Lawrence, August 1930

Considerable difficulty was experienced in refining certain crude due to corrosion on the crude tube stills and the battery of cracking units. On the cracking stills, this rapid corrosion soon gave rise to failure in tubes, return beds, headers and transfer lines. Immediately, several methods were implemented to reduce the corrosion rate, one being to employ hydrated lime. The lime treatment was chosen because enough of the alkali could be fed into the stills with the charging stock to greatly reduce the corrosion and still not be detrimental to the stills.

Few concerns dominate refining capacities

G. Reid, September 1930

Twenty-two companies own nearly 80% of the total crude capacity and 87% of the cracking facilities in the U.S. These 22 companies have 159 refineris and 1,713 cracking units. The remainder of the refining capacity (20%) is divided among approximately 275 plants owned by close to 250 companies. These companies possess about 290 cracking units.

The refining industry, like several other industries, is dominated by a score of companies. However, compared to other industries such as automotive, public utility and steel, the petroleum refining industry is divided among a relatively large number of competitive units.

Transportation by land, water and air

E. V. Rickenbacker, October 1930

In less than a generation, we must expect improvements in transportation by highways, water and air far beyond anything dreamed by the public. This could include traveling by superhighways 300 ft–400 ft wide, extending from ocean to ocean and from border to border. Commercial air travel can one-day bring hordes of passengers to faraway places and much more; the possibilities are endless.

The meaning of the gasoline distillation curve

G. Edgar, J. B. Hill and T. A. Boyd, November 1930

The purpose of this paper is to discuss the more important relationships between the distillation data of gasoline and its performance in the automobile engine. Motor fuel volatility relates to engine performance in the following ways:

- Ease of starting a cold engine
- Tendency to interrupt operation because of vapor lock
- Ease of acceleration
- Relative ease of effecting a dry mixture
- Tendency to crankcase dilution.

A study of the fundamental principles involved leads to several practical principles that may serve as a guide to oil refiners in indicating the volatility characteristics which gasoline should pos-

sess to give satisfactory engine performance under various conditions, and to the automotive engineer in indicating methods by which the fuel fee systems of automobiles may be improved.

More cracking units—Less straight-run gasoline production

C. F. Kettering, January 1931

Straight-run gasoline is fast losing its prestige. Because of its anti-knock qualities, cracked gasoline is steadily progressing in importance.

Possible use of natural gas for chemicals

H. Smith, January 1931

A significant amount of natural gas is wasted from in oil field operations/production. One possible method of utilization is in the manufacture of chemical products.

Vapor distillate stabilization and gas recovery system

A. W. Burket, March 1931

This article presents data and yields of petroleum products from various crude runs on a modern continuous vacuum distillation battery. The distillation of a given cut of oil can be carried out at an appreciably lower temperature under vacuum than under atmospheric pressure. The prime advantage of this is prevention or reduction of undesirable cracking. Therefore, heavy lubricating oils of high flash can be obtained. Another advantage is in smaller fuel bottoms yields are made possible by vacuum reduction. This means greater available yields of cracking stocks. From a mechanical standpoint, the use of vacuum by lowering distillation temperatures results in reduced deterioration of still bottoms by heavy firing.

Corrosion-proof pressure vessels

O. E. Andrus, April 1931

To help mitigate corrosion on pressure vessels, a new method has been developed which coats the entire vessel in a corrosion-proof alloy.

Progress toward a standard method for determining the anti-knock value of motor fuels

H. C. Dickinson, May 1931

Tests show that anti-knock characteristics of commercial motor fuels can be determined. These measurements are likely to be of increasing importance because of the rapid changes in motor design, and consequently in fuels, required to meet the motoring public's demand for increased power.

Waste fuels develop steam and electricity

H. R. Sharpless, July 1931

The author, Superintendent of Power, Gulf Refining Co., Port Arthur, Texas (U.S.), details the utilization of waste materials for the generation of steam and electricity. He cites some of the problems of generation and means of solution as experienced at the largest refinery in the world.

Direct cracking of crude

E. F. Nelson, August 1931

This work focuses on the cracking of light crudes when charged direct to the latest type of the Dubbs cracking unit.

Shield welded pressure vessels now safe for all hazardous uses

G. Raymond, December 1931

Of great importance are the remarkable improvements in the art of electric arc welding known collectively as "shielded welding processes." By means of these greatly advanced welding processes, joints of nearly 100% efficiency can be rapidly formed between parts of almost any thickness or shape.

Anti-knock characteristics of natural gasoline with reference to grading

R. C. Alden, February 1932

By chilling the fuel systems of knock testing engines, it is possible to determine the anti-knock ratings of gasolines of comparatively high vapor pressure. A limited number of such determinations have been made on natural gasoline and the results have been correlated with other characteristics of the gasoline. The best relationship has proven to be with Reid vapor pressure.

Skimming, cracking and reforming accomplished in one furnace

C. J. Pratt, March 1933

Simplicity is the essence of modern invention. The recently perfected petroleum refining process that incorporates simultaneous skimming, reforming, vapor phase cracking and rerunning is discussed in this article.

Octane requirements forcing cracking expansion

G. Reid, April 1932

The future of the refining industry is closely interwoven with the future progress made in the development of the cracking process. The refiner that does not possess cracking facilities will find it increasingly difficult to compete and to market their relatively low anti-knock rated motor fuels.

Integrated units controlling more refinery capacity

G. Reid, May 1932

Refining capacity continues to shift toward the integrated company. Regardless of the economics of the situation, more refining companies are engaging in the marketing of petroleum products, and more refineries are being erected by the integrated refining company.

Modern design in cracking facilities

J. J. Mack, October 1932

The trend in cracking unit design is not only toward larger capacities but includes the use of multiple furnaces, wherein two cracking coils discharging into a common secondary system lend much to flexibility of the installation. This article describes the design and operating features of this modern-style plant.

Survey of cracking plants shows continued expansion

G. R. Hopkins, October 1932

Role of sulfuric acid in the treatment of pressure distillate

A. W. Trusty, December 1932

Although various treating methods have been put into commercial operation in the last 10 yr, the sulfuric acid method of

treating petroleum naphtha continues to be the most widely used. This article provides the advantages and disadvantages of treating cracked distillate with sulfuric acid.

Design of treating system includes facilities for purging

January 1933

Preparation of ethyl alcohol from ethylene

V. Gerr, O. Pipik and E. Mezhebovskaya, February 1933

In this series of articles, information is presented dealing with the preparation of ethyl alcohol from petroleum gases both in the laboratory and in commercial scale. Ethylene was separated from the homologs by making use of the selective absorption ability of activated charcoal and separated in the form of ethyl sulfuric acid and the alcohol separated by hydrolysis. Silver and iron catalysts were used to accelerate the reaction. The constants of the synthetic alcohol coincide with those of fermentation alcohol.

Meeting some of the problems of the pressure vessel user

T. McL. Jasper, O. E. Andrus and L. J. Larson, April 1933

The history of pressure vessel development can be characterized by a series of increasing demands by the pressure vessel user, which have been met by the pressure vessel manufacturer.

The invention of the steam engine marks the starting point in the demand for pressure equipment on a quantity basis. This demand started on a relatively small scale and has expanded into the use of large quantities of steel and other materials. Many different methods of factrication have been used for producing pressure vessels. Cast iron, bolted and riveted wrought materials, forge welded cylinders, solid forgings and, most recently, autogenous welded vessels have marked the general history of the development.

Tube wall telescope for examination of interior of tubes and piping

May 1933

This article details an invention that enables plant personnel to examine the inside of tubes and piping.

Development of naphtha reforming practice for octane number improvement

E. J. LeRoi and H. W. Ferguson, June 1933

Naphtha reforming is a direct outgrowth of the ever-increasing demand for higher octane number motor fuels. Since the refiner has been dependent in the past on selection of crudes and blending fluids for anti-knock improvement, the application of naphtha cracking lends greater flexibility to refinery operations. This article details three years of experimental work on both straight-run and cracked heavy naphtha. The combined and individual effects of time, temperature and type of feedstock on yield, capacity and product quality have been carefully analyzed for varying degrees of octane number improvement.

Removal of hydrogen sulfide from high-sulfur gases

P. J. Wilson, July 1933

This article details three new processes—developed in the past year—to remove hydrogen sulfide from high-sulfur gases.

Comparison of cracking and hydrogenation as methods of producing gasoline

R. T. Haslam, R. P. Russell and W. C. Asbury, September 1933

This article focuses exclusively on the use of the hydrogenation process for gasoline production from gasoil. A critical analysis has been made of the factors which affect the economic position of the hydrogenation process, the ability of the process to compete with cracking and its use in conjunction with cracking.

Automatic temperature control in oil refining

V. R. Chadbourne and P. E. Darling, December 1933

Deviations from optimum operational conditions result in decreased yields, shortened runs and a departure from the desired product specifications. Modern refining units have variables such as flow, furnace temperatures, outlet temperatures and tower levels held within very close limits by automatic devices. Any control that will increase the yield by a fraction of one percent, even though of high initial cost, will be paid for by the increased yield in a remarkedly short time.

Design of high-pressure rectifiers

I. N. Beall, March 1934

This series of articles focuses on high-pressure rectifiers that are in use for the stabilization of natural gasoline.

Regular grade cracked gasoline and "Q" grade ethyl compared

W. Hubner and G. B. Murphy, May 1934

While the octane number method of rating gasoline quality has become generally reconfirmed and accepted by the automobile and oil industries, doubts have been growing in the minds of many technologists as to the adequacy of this method as the only criterion on which to measure the value and base the price of motor fuel. Because of these doubts, road and laboratory dynamometer tests were made in which the performance of cracked gasoline from one refinery, undoped, was compared against "Q" grade gasoline of equal volatility and equal octane rating.

The tests showed that there are desirable performance properties not shown by octane number tests, primarily miles per gallon and horsepower hours per gallon. Conclusions drawn from the road and laboratory tests showed non-ethylized regular-grade cracked gasoline is a motor fuel superior to "Q" grade ethyl of equal volatility and equal octane number rating.

Fouling of heat exchangers

W. L. Nelson, July 1934

These articles focus on the fouling of heat exchangers and the fouling factors which are obtained in classes of heat transfer equipment. Part 1 provides an introductory to heat transfer and fouling, with Part 2 focusing on fouling factors that can be expected in plant service, the deposition of coke in pipe still tubes, the temperatures that are attained in pipe still tubes and the fouling conditions caused by hard water and wax.

Prospects of a petroleum chemical industry

C. Ellis, September 1934

During recent years, there has been a steady trend toward the establishment of a chemical industry dependent upon petroleum as a source of raw material.

The efficiency of petroleum fractioning column

V. W. Garton and R. L. Huntington, January 1935

Separation of crude oil into its several cuts by means of fractional distillation is one of the most important processes used in the petroleum refining industry. This process depends on four factors:

1. The number of bubble plates
2. The molar ratio of reflux, or overflow to the rising stream of vapor
3. The approach toward equilibrium conditions between liquid and vapor of each plate
4. The amount of entrainment or mechanical carrying of liquid droplets or mist from one plate to another.

This article provides a simple method to determine the fractionation capacity of any laboratory packed column, a knowledge of which is essential in the analysis of fractions from commercial towers and in the calculation of their efficiencies.

The trend in design, construction and operation of gasoline plants

J. Campbell, March 1935

The author states, "The modern natural gasoline plant is quite different from the plant of yesterday, but the plant of tomorrow will be better arranged, even more completely automatic—if such an expression may be used—and less wasteful, as well as more efficient and safer. However, we will have the personal element to contend with as long as human beings must operate and watch over operations. Each of us who has any responsibility for the construction and operation of these plants should adopt as their personal motto and pass on to all those under their supervision this slogan, 'eternal vigilance is the price of safety'."

Inspection of oil refinery equipment

F. Newcomb, April 1935

Inspections should not be conducted by those directly responsible for the production or maintenance of equipment. Thorough inspections should be conducted by independent forces, with the freedom to state conditions exactly as found and to criticize the condition of the equipment without fear of jeopardizing their positions. This structure can lead to optimal operation of refining equipment.

Fuel specifications for high-speed Diesel engines

G. C. Wilson, June 1935

The development of the high-speed Diesel engine depends as much upon proper fuel specifications as upon engine design. Therefore, refiners and engine builders will find it advantageous to cooperate in solving fuel problems.

The various items included in specifications are discussed here. The importance of ignition quality and its effect on engine operation are emphasized.

Cost of steam and heat in the refinery

W. L. Nelson, April 1936

Steam and heat are the most important items in refining operations and the proper utilization, conservation and distribution of steam and heat influences the profit and loss of a facility. This series of articles focuses on the economics of steam and heat usage within a refinery.

Instrumentation in oil refining

A. C. Proctor and G. Egloff, June 1936

One of the important developments in the processing of oil has been in automatic control. This development has brought about marked economic savings due to producing better and higher yields of the more valuable products from crude oil.

Natural gas as a chemical raw material

I. N. Beall, July 1936

Natural gas consists of relatively few components, and these are easily separable in substantially pure form by methods already established. In most chemical processes, the purity of the basic raw materials is of considerable importance. In this article, the author examines processes that could utilize natural gas for chemicals production.

Salt removal from crude oil—Chemical and physical methods

E. R. Jones, May 1937

This article discusses the observations made and the results obtained while trying to find an immediate practical solution for removing salts from crude oil.

Cathodic protection: Its application in refineries

D. S. Sneigr, July 1938

Cathodic protection of metals has been found worthwhile in protecting pump shafts. Refinery and other tank farms use it for protection of large tank bottoms, and its use has extended to all types of pipelines for carrying oil, natural gas, refinery gas, water and many others. This article reviews the development of cathodic protection and describes the various types of equipment and systems available and in wide usage.

Lower paraffins over activated alumina catalysts

J. Burgin, H. Groll and R. M. Roberts, October 1938

Increasing demands for lower olefins as base materials for synthetic gasoline and chemical products have led to the investigation of catalytic dehydrogenation processes for their production from lower paraffins. This article provides results of experiments with activated alumina, alone and combined with chromium oxide, which has proved to be a selective catalyst for dehydrogenation.

Preparation of blending stock for 100-octane gasoline

L. J. Coulthurst, March 1939

Aviation gasoline having a 100 octane anti-knock rating has become established as an economic reality within the last 2 yr and is no longer regarded as a laboratory curiosity. There is no doubt that commercial planes will be using 100-octane motor gasoline exclusively in the very near future. HP

LEE NICHOLS, VP, Content/Editor-in-Chief

The 1940s: Global conflict, FCC, 100 octane, synthetic rubber—Wartime necessitates advancing technologies

Hydrocarbon Processing continues its look at the history of the hydrocarbon processing industry (HPI). The first installment detailed the origins of the global refining and petrochemical industries, followed by major refining and petrochemical discoveries of the 1930s, including the discovery of catalytic cracking and polyethylene; the evolution of coking and gasification; the production of polystyrene, nylon, polyester, resins, epoxies and polyurethane; and the inception of the jet engine.

The following will detail how the HPI continued to evolve during the 1940s.

The onset of fluid catalytic cracking (FCC). In 1936, Eugene Houdry started up the first Houdry unit at Sun Oil's Marcus Hook refinery in Pennsylvania (U.S.). The novel fixed-bed catalytic cracking unit was instrumental in evolving the gasoline production process. For example, approximately 50% of the 15,000-bpd unit produced high-octane gasoline, which was double the production of conventional thermal processes.[24] However, the novel Houdry process—a significant advancement vs. the thermal cracking process—was unable to satisfy increasing global demand for gasoline from vehicles and the aviation industry.

In the early 1940s, Standard Oil of New Jersey and Davison Chemical (the company would later become W. R. Grace & Co.) collaborated on developing powered catalyst and an improved catalyst circulation design vs. the Houdry process. The companies were joined by the Massachusetts Institute of Technology (MIT) and M. W. Kellogg.[23]

Through significant research, MIT professors Warren Lewis and Edwin Gilliland improved Houdry's design. One of the major changes was improving catalyst circulation—the new design enabled the catalyst to pass through both the reactor and regenerator. Their patent was the basis for Standard Oil of New Jersey's 100-bpd pilot plant in Baton Rouge, Louisiana (U.S.).[23] The newly designed pilot plant was tested and, after a few modifications, was shut down and redesigned into a full commercial unit. On May 25, 1942, Powdered Catalyst, Louisiana 1 (PCLA) Model 1 went online (**FIG. 1**), marking the first use of a commercial catalytic cracking process using powdered catalyst.[23] The plant's catalyst was supplied by Davison's Curtis Bay Works facility in Maryland, which also began operations in May 1942—three months later, *The Refiner and Natural Gasoline Manufacturer,* the forerunner to *Hydrocarbon Processing,* was retitled *Petroleum Refiner;* the name change reflected the significant advancements and broader scope of petroleum processing. The Curtis Bay plant was the world's first synthetic FCC production facility, and, in 1947, Davison established the refining industry's first technical services facility for fluid cracking catalysts.[47]

Over the next 2 yr, several new FCC units were built in the U.S. The new refining process helped to significantly increase production of gasoline motor fuel and aviation gasoline, which was crucial in aiding the Allied powers in World War 2 (WW2).

The world engages in conflict. On September 1, 1939, Germany invaded Poland. The invasion caused European allies to mobilize against Germany, setting off the largest and bloodiest conflict in human history. Central to both the Allies and Axis powers' military operations was the ability to produce refined fuels. Oil and refined

FIG. 1. View of Standard Oil of New Jersey's PCLA Model 1 plant in Baton Rouge, Louisiana—the first use of a commercial catalytic cracking process using powdered catalyst. Photo courtesy of the American Chemical Society.

fuels were imperative during the war. Without fuel (gasoline and aviation gasoline), tanks could not run, planes would not fly, battleships and other marine vessels are trapped in port, and thousands of other vehicles (e.g., jeeps) become obsolete. Oil was also indispensable for lubricating guns and machinery both in the field and to fuel domestic industrial manufacturing.

The Allies—especially the U.S.—controlled most of the world's oil production. Conversely, Germany lacked any kind of oil production, which was a major factor that eventually led to its demise. However, Germany did have a substantial amount of coal reserves. To fuel its war machine, Germany primarily used coal conversion processes for synthetic-fuels manufacturing. More than 90% of Germany's aviation gasoline and half of its total domestic petroleum products production came from synthetic fuel plants.[48] These plants primarily used the Bergius process and the Fischer-Tropsch process, among others.

FIG. 2. The British Spitfire used 100-octane fuel-powered Rolls-Royce Merlin engines, enabling them to gain a decisive advantage over the German Luftwaffe during the Battle of Britain in WW2. The U.S. significantly boosted 100-octane fuel production, enabling the Allies to gain air superiority against the Axis powers. Photo courtesy of the Imperial War Museum.

FIG. 3. WW2 poster stressing the importance of high-octane aviation fuel. Spoken by U.S. Chief of Naval Operations Ernest King, the slogan "Oil is ammunition" was used for promotional posters during the conflict. Source: U.S. National Archives and Records Administration.

Japan suffered from the same challenge as Germany. The country had no oil production and virtually no refining system to produce fuels for its war effort. Japan did have major coal reserves and tried to venture into synthetic fuels production; however, it lacked the technical expertise and specific alloys and catalytic metals required for synfuel production.[49]

Once the U.S.—the primary supplier of oil and finished products to Japan—cut off oil supplies to the island nation, Japan began a strategic military offensive in the South Pacific, seizing oil fields developed by Royal Dutch Shell in the Dutch East Indies (i.e., Indonesia) and Borneo, which also contained 90% of the world's natural supply of rubber.[49] However, the Axis powers could not compete against the manufacturing juggernaut of the Allied nations.

Several new technologies and initiatives were integral in the Allied war effort against the Axis powers. These included the production of 100-octane aviation gasoline, a boost in domestic refined fuels capacity, a more efficient way to produce pure toluene and cooperation for the development of synthetic rubber.

100 octane: A decisive advantage in aerial superiority. In the mid-1930s, U.S. aviator Jimmy Doolittle joined Shell Oil Co. as Aviation Manager. His primary responsibility was to develop aviation fuels for military and civilian applications. Up until this time, both automobiles and aircraft ran off 87-octane gasoline levels. However, the lower-rated fuel severely affected aircraft engine performance, negatively impacting speed, climb rate, service ceiling and overall performance, especially at higher altitudes. Higher octane aviation gasoline (i.e., 100 octane) could fuel high-performance aircraft engines, boosting the performance of fighter planes.

After lobbying the U.S. Congress, Doolittle convinced the U.S. Army to adopt 100-octane aviation fuel as the standard fuel for aircraft. However, the fuel was extremely expensive to produce and prohibitively high to sell—the cost of 100-octane fuel was approximately \$20/gal vs. less than \$0.20/gal for regular automobile gasoline.[50] The solution to this challenge came from a new process in operation at the Marcus Hook refinery in Pennsylvania. The process was a catalytic cracking process developed by a French engineer: Eugene Houdry.

The Houdry process was greatly enhanced by octane-boosting processes, the most notable being invented by Russian-born chemists Herman Pines and Vladimir Ipatieff. Ipatieff, the Director of Chemical Research at Universal Oil Products (UOP) and a professor at Northwestern University in Chicago, was responsible for the development of solid phosphoric acid—a highly active refining catalyst created by treating silica with phosphoric acid.[51] The catalyst was instrumental in increasing octane levels of gasoline. Ipatieff worked closely with fellow UOP colleague Herman Pines in the 1930s. The pair were instrumental in developing new polymerization, alkylation of aromatic compounds (i.e., alkylation)—Phillips (later called ConocoPhillips) invented the hydrofluoric acid (HF) alkylation process in the early 1940s to produce high-octane aviation gasoline[52]—and isomerization of paraffins (i.e., isomerization) to boost octane levels in aviation gasoline to 100. These new processes enabled the U.S. refining industry to produce affordable high-octane aviation gasoline, which would play a decisive role in WW2.

By 1940, the U.S. was producing more than 4.2 MMgpm of 100-octane aviation gasoline[53]—the standard fuel for the U.S. Air Force (referred to as the U.S. Army Air Corp prior to entrance in WW2). As war was declared in Europe, the U.S. gained its first customer for 100-octane aviation gasoline: Great Britain. The high-octane fuel powered Rolls-Royce Merlin engines inside British Hurricane and Spitfire fighter planes (FIG. 2), enabling them to gain a decisive advantage over the German Luftwaffe—most of Germany's fighter planes ran on 87-octane aviation gasoline. The 100-octane aviation fuel was an invaluable asset that helped Britain push back German air attacks during the Battle of Britain and aided Allied powers in establishing air superiority (FIG. 3).

TNT. Trinitrotoluene (TNT) was first discovered by German chemist Julius Wilbrand in 1863. However, the first use of the material was for yellow dye. Approximately 30 yr later, German chemist Carl Häussermann discovered its explosive properties.[54] TNT was used by Germany and other militaries starting in the early 1900s.

According to literature,[55] Standard Oil

Development (the company would later become Exxon) detected toluene in product streams from thermal reforming experiments on a petroleum-based naphtha. This discovery led to a new source to produce a significant amount of pure toluene. However, the produced product did not meet nitration-grade requirements. Upon using catalytic reforming, the process produced a 99+% toluene stream that could be nitrated.[55] From 1940–1945, toluene production in the U.S. topped 484 MMgal, with nearly half being produced by Standard Oil's subsidiary, Humble Oil and Refining Co. Approximately 15% was produced by Shell.[56] This significant increase in production enabled the Allied powers to receive a steady stream of explosive materials.

Synthetic rubber. Although the discovery of synthetic rubber dates to the late 1870s (French chemist Gustave Bouchardat created a polymer of isoprene), the first true synthetic rubber was created and patented by German chemist Fritz Hofmann in the early 1900s.[57] During WW2, the Allies were nearly cutoff from supplies of natural rubber—the Japanese occupied rubber producing areas in Southeast Asia, which represented 90% of the world's natural rubber production.[58] Without rubber, Allied vehicles and planes could not be built or repaired.

As a solution, the U.S. government partnered with four rubber companies—B. F. Goodrich, Firestone Tire and Rubber Co., Goodyear Tire and Rubber Co, and the U.S. Rubber Co. (the company would later become Uniroyal)—to find a solution to the rubber supply crises. However, to produce synthetic rubber, butadiene—its basic raw material—is needed. To produce much-needed supplies of butadiene, several U.S. refiners built new facilities to produce the product that would be used to increase synthetic rubber production.

Researchers at the four big tire companies set out on new processes to increase synthetic rubber production in the U.S. In 1940, while working at B. F. Goodrich, Waldo Semon—the inventor of an improved process for PVC production—invented a process for the copolymerization of butadiene with methyl methacrylate. The cost-effective synthetic rubber produced was marketed under the name Ameripol. Goodyear produced its own synthetic rubber—the process was patented by Ray Dinsmore—called "Chemigum." The other rubber companies patented processes to increase synthetic rubber production, as well.[59]

However, in 1942, synthetic rubber producers were needed to boost production to aid the Allied war effort. The four rubber companies, along with the U.S. government, agreed upon a common process to produce synthetic rubber called GR-S (government rubber styrene), which was similar to Bina S developed by Germany. By 1945, the U.S. increased GR-S production to approximately 920,000 tpy.[59] Due to this manufacturing juggernaut, Allied forces did not suffer from a shortfall in synthetic rubber for military equipment and vehicles.

Cyanoacrylates. In 1942, Harry Coover—while working at the Eastman Kodak company in the U.S.—was conducting experiments with cyanoacrylates. He was attempting to develop materials to build clear plastic gun sights for the Allies

in WW2. However, while working with the materials, he noticed that it stuck to everything, making it very difficult to work with. According to literature, moisture caused the chemicals to polymerize, and since virtually all objects have a thin layer of moisture on them, bonding would occur in nearly every testing instance.[60] Since the material was highly adhesive, the researchers rejected the commercial use of it.

It was not until 1951 that Coover and fellow researcher Fred Joyner recognized the potential of cyanoacrylates as a quick bonding substance. His team was researching heat-resistant polymers for jet airplane canopies. These tests showed the unique adhesive properties of cyanoacrylate—the adhesive required no heat or pressure to bond.[60] Several years later, Eastman Kodak sold the material as Eastman 910, later marketing the material as it is known today: Super Glue. The material—still in use today for many applications—has a unique story in that it was discovered by accident, twice.[61]

Silicones. Although discovered in the 1850s, commercial silicones research and development would not take off until the 1930s. Early research was conducted by American chemist James Franklin Hyde while working at Corning Glass Works (FIG. 4). By using English chemist Frederic Stanley Kipping's procedure for creating organic silicon compounds, Hyde was able to create a synthesized fluid that hardened into a rubbery mass.[62] Kipping pioneered work in silicone polymers, even coining the name "silicone" in 1904.

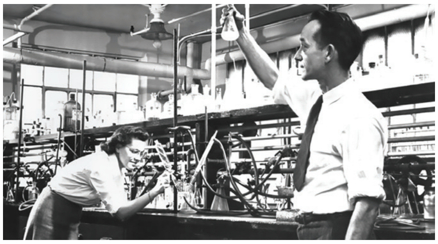

FIG. 4. James Franklin Hyde works with a colleague on experiments in the Corning Glass Works' lab. Photo courtesy of Dow Corning.

Hyde's discovery enabled Corning to produce high-temperature motors and generators. Silicones were used extensively in ships and planes during WW2 as a cable and wire insulator.[62] Hyde's work created the first commercially useful silicone product and led to the formation of the Dow Corning Corp. in 1943—a JV between Dow Chemical Co. and Corning Glass Works. The company's primary focus was to develop silicone products, including manufacturing products for the U.S. military in WW2. The company's first product was Dow Corning 4, an ignition sealing compound that made high-altitude flight possible. The compound prevents corona discharge, enabling aircraft to remain at 35,000 ft for 8 hr. This benefitted the Allied powers since planes could be flown to the UK and North Africa vs. transporting them by ship, significantly reducing the risks of them being bombed and destroyed by Axis forces.[63,64]

Silicone continues to be widely used in many different industries and applications, including in automotive, construction, energy, electronics, chemicals, coatings, textiles and personal care, among others.

Unconditional surrender and post-war discoveries. On May 7, 1945, Germany unconditionally surrendered to the Allies. Japan did the same on September 2, 1945. These events marked the end of the 7-yr global conflict.

The end of the European conflict also saw the breakup of the largest chemical and pharmaceutical company in the world, IG Farben. The company was formed in 1925 as a merger of six chemical companies—BASF, Bayer, Hoechst, Agfa, Chemische Fabirik Griesheim-Elektron and Chemische Fabrik vorm. Post WW2, the company was broken into several different entities. Agfa, BASF and Bayer continued operations. Hoechst acquired several other companies over the next several decades, as well as spinning off portions of its business into independent companies, such as Clariant. Hoechst is presently a subsidiary of the French pharmaceutical company Sanofi.

Although WW2 had ended, the global refining and petrochemicals industries were just beginning. New technologies and discoveries continued to be made through the rest of the 1940s.[65] In 1947, American chemical engineer Vladimir Haensel conducted experiments using platinum catalysts for upgrading petroleum. However, at the time, the use of platinum catalyst was thought to be impractical and uneconomical due to the costs of the precious metal. Haensel's research showed that using miniscule amounts of platinum (0.01%) was enough for an effective process.[66,67] This research led to a novel process to produce gasoline with a higher octane rating: Platforming. Haensel's Platforming process also generated a higher yield of aromatic hydrocarbons, which are used in manufacturing plastics.[66,67] The process was commercialized by UOP, and the first Platforming unit (FIG. 5) was built in 1949 at Old Dutch Refining Co.'s refinery in Michigan (U.S.). The Platforming process was instrumental in the eventual removal of lead from gasoline.

FIG. 5. Vladimir Haensel (left) developed the Platforming process. The first Platforming unit (right) went online in 1949 at Old Dutch Refining Co.'s refinery in Michigan (U.S.). Photo courtesy of Honeywell UOP.

The 1950s. Post-WW2 saw a significant increase in oil consumption and economic development in Europe and the U.S. New chemical and refining discoveries would continue to improve the lives of people around the world. The evolution of the global refining and petrochemicals industry in the 1950s will be examined in the next installment. HP

LITERATURE CITED

Complete literature cited available online at www.HydrocarbonProcessing.com

LEE NICHOLS, VP, Content/Editor-in-Chief

Operations expand and technologies advance during global conflict: Excerpts from the 1940s

Application of x-ray inspection on oil refining equipment

H. R. Isenburger, January 1940

This articles details several case studies on the use of x-ray technology for inspection purposes. This includes for the inspection of casings, forgings and welded structures, among others.

Calculating gasoline octane rating from gravity and ASTM distillation

R. B. Cox, February 1940

Determining the octane number of gasoline is an expensive and time-consuming operation. Many attempts have been made to correlate this octane number with various physical properties of gasoline. The purpose of this paper is to present methods of calculating the octane rating of any gasoline by using only its API gravity and ASTM distillation.

Synchronized controls improve boiler operation

May 1940

Synchronizing the controls in the boiler room of a gasoline plant was accomplished through an arrangement of valves, piping and linkage, so that the draft through each boiler is automatically adjusted to the quantity of steam generated and the amount of fuel consumed.

Aviation gasoline plant near the Arctic Circle

R. E. Parkhurst, July 1940

This article examines the completion of the northern-most refinery in operation. The 840-bpd refinery has been developed by Imperial Oil Ltd. The facility is located at Norman Wells on the Mackenzie River in Northwest Territories, Canada, approximately 100 mi from the Arctic Circle.

The behavior of gasoline-coal fuel in spark-ignition engines

J. E. Hedrick, August 1940

Discussions have been made regarding the use of petroleum and pulverized coal mixtures in internal combustion engines. This subject has received more attention in Europe because of the scarcity of motor fuels. This work presents data on actual engine performance where a gasoline-coal suspension was used as fuel vs. the use of only gasoline.

Butyl rubber—A new hydrocarbon product

R. M. Thomas, I. E. Lightbown, W. J. Sparks, P. K. Frolich and E. V. Murphree, October 1940

In developing their new butyl rubber, Esso Laboratories has turned to simple olefins rather than diolefins or more complicated chemical derivatives as the primary raw material. Not only is this an economic advantage, but the availability of such simple olefins from refinery cracking operations makes the process attractive to produce synthetic rubber.

Use of additives in automotive lubricants

F. L. Miller, W. C. Winning and J. F. Kunc, February 1941

Only a few years ago, it was predicted that the motor lubricant of the future would consist of a highly refined mineral-oil base to which small quantities of special chemical agents would be added to secure the properties desired for superior engine lubrication. Today, progress in this direction is so rapid that it appears to be only a matter of time until most, if not all, of the predictions are realized.

The study of water problems in atmospheric cooling systems

D. W. Hearing and D. M. Considine, March 1941

Solutions to challenges in atmospheric water cooling systems in petroleum refining are receiving closer attention because expansion of processes and consequent increased demands of cooling have stimulated the trend toward water conservation through the installation of recirculating water systems.

Production of aviation motor fuel from natural gasoline

K. E. Cody and D. M. Luntz, April 1941

For many years, the principal use of natural gasoline has been to raise the volatility of motor fuel. Consequently, natural gasoline has been sold on a vapor pressure-volatility basis with little regard for other characteristics such as octane blending value and lead susceptibility. With the increased demand for high-octane aviation gasoline and with the depressed market for natural gasoline, many plants are considering manufacturing aviation base stocks as a means of making a larger profit on their production.

Useful products from natural gas

F. H. Dotterweich, May 1941

The growth of natural gasoline production has increased the amount of the byproduct natural gas, which has been marketed as a fuel and source of energy. More recently, natural gas has been used as a raw material for chemical production.

First hydroformer unit put on stream

J. V. Hightower, May 1941

The 7,500-bpd hydroforming unit went online at Pan American Refining Corp.'s refinery in Texas City, Texas (U.S.). The unit is the first commercial installation of this type. It uses a catalytic process to convert low-octane naphtha into 77–80 octane aromatic gasoline containing a small percentage of unsaturates.

Petroleum becomes source of military explosives

B. O. Lisle, August 1941

Trinitrotoluol (TNT) is a preferred explosive because of its high power, great stability and dependability, and safety during handling. The increasing demand for TNT has resulted in the increased demand for toluene. This article looks at what toluene is, and the different processes used to manufacture it.

Refining processes

September 1941

This section was the forerunner to the publication's Refining Handbook. This first iteration details more than two dozen refining processes used in the early 1940s, including distillation, alkylation, catalytic cracking, catalytic polymerization and isomerization, among others.

Turbines for power generation from industrial process gases

J. Goldsbury and J. R. Henderson, December 1941

This article presents the files of application for turbines operated by industrial process gases and natural gases. It provides examples of mechanical details of actual turbines which have been built for such applications, a simple method for calculating the energy available in a pure or a compound gas for specific operating conditions, and the properties of various gases for use in such calculations.

Defense efforts push oil to record levels during 1941

W. R. Boyd, January 1942

Natural gas as a raw material in the production of synthetic ammonia

F. H. Dotterweich, March 1942

Butadiene calls for few departures in equipment or processing

J. V. Hightower, April 1942

Although the petroleum refining industry is turning to the production of raw materials, chiefly butadiene for the manufacture of synthetic rubber, this does not mean that plants will require radically different equipment and fundamentally different processes from those used in the production of ordinary petroleum products.

Importance of butane in this war

R. L. Huntington, May 1942

Natural gasoline manufacturers realize the important part that butanes are playing in the production of materials highly essential for winning the war. Through thermal and catalytic conversion processes, isobutane is being made into isooctane, an invaluable blending agent for aviation motor fuel. Normal butane is being converted into butadiene through dehydrogenation. Approximately three parts of butadiene and one part of styrene make up the principal constituents going into the manufacturing of artificial rubber.

Increasing recovery of liquefied petroleum gases in natural gasoline plants

J. W. Wilson, June 1942

Total sales of LPG have significantly increased over the past 2 yr. The increasing uses for these petroleum gases are leading to accelerating demand.

Practical methods for storing volatile liquids

D. E. Larson, July 1942

In designing a chemical plant or petroleum refinery, provisions must be made for the storage of volatile liquids. The designer will naturally design storage capable of the following results:

1. Retaining each product for the required period without deterioration or loss of quality
2. Retaining the product without loss of volume
3. Storing the product at the lowest possible cost per gallon commensurate with safety
4. Storing the product with the least possible danger from fire.

The War Products issue

October 1942

This issue was dedicated to petroleum products produced to help the Allies during World War 2. The issue focuses on the different processes that produce products such as synthetic rubber, aviation gasoline, aviation lubricants, toluol, alcohol, plastics, etc. The introduction of the issue is copied below:

"Upon their supply and performance rests the fate of civilization. Equally important will be their influence upon human affairs in the peace to come. Petroleum refining rises to meet this challenge and marches on to victory.

The following pages illustrate the present and the future. Photographs show the rubber consuming instruments of war for which the industry's hectic planning and building are being made and the products/fuels produced to excel in battle. The story tells of the peacetime future of these wartime products."

Record crude production and high refinery runs required to meet huge military needs

L. J. Logan, August 1943

Fluid catalyst cracking for premium fuels

E. V. Murphree, H. G. M. Fischer, E. J. Gohr, W. J. Sweeney and C. L. Brown, November 1943

Many large fluid catalyst cracking units are in operation producing highly aromatic aviation basestocks, raw materials for alkylate, synthetic rubber and toluene. These operations have established the fluid catalyst process as an economical basic cracking installation for producing aviation and motor fuels.

Recent developments in Houdry fixed-bed catalytic processes

T. B. Prickett and R. H. Newton, November 1943

This paper provides developments by which the original fixed-bed Houdry process was adapted to produce basestock for aviation gasoline. Among the developments were the manufacturing of synthetic catalyst, production of isobutane and butylene for alkylation and catalytic treating of primary basestock.

How will the 100-octane aviation gasoline program affect post-war motor gasoline?

B. K. Brown and D. P. Barnard, December 1943

With the return of competition in cost, processes and raw materials, the authors of this article are of the opinion that: "As much as 100,000 barrels of 100-octane capacity will be shut down or diverted to other uses because of excessive operating costs and crude utilizations."

Bombs fall on Ploesti

March 1944

"For the Ploesti mission, every plant in each element was given a pinpoint and had to find it. There are no secondary targets." This quote—said Lieutenant B. O. Lisle during the annual meeting of the American Institute of Mining and Metallurgical Engineers—summed up the bombing of refining centers in Ploesti, Poland by Allied bombers. Refined fuels were crucial in aiding the war effort on both sides. Without oil/fuels, military operations could not be conducted.

Study of the effect of catalytic cracking on the post-war supply of motor gasolines, distillates and residual fuels

March 1944

Previous advances in refining technology have been slowly adopted. Necessity for military-grade gasolines brought catalytic cracking into refining without regard to other considerations. With the end of fighting, catalytic cracking capacity, the quality of its products, its ownership and its location will suddenly become factors in what the industry has to sell.

Use of the mass spectrometer in the routine analysis of refinery gas samples

J. G. Schaafsma, April 1944

This article provides a brief discussion on the theory and operation of the mass spectrometer and its performance when used to control and acid alkylation unit.

How to train plant personnel in fire prevention and fire fighting

A. W. Trusty, May 1944

Refining personnel is changing rapidly and many new personnel have never seen an oil fire. It is imperative that operators be familiar with the cause and nature of fires, along with the most efficient and quickest methods to combat them.

Influence of ozone on diesel engine performance

W. J. Armstrong and C. E. Thorp, June 1944

For several years, ozone has been suggested as an agent that might be of value in obtaining improvement in the thermal efficiency of internal-combustion engines. This paper describes various experiments to determine the influence of ozone on compression-ignition engine performance.

Chemicals from petroleum

H. D. Wilde, July 1944

The outstanding raw material used today for synthetic chemical production, especially from a volume standpoint, is butylene.

Time-saving computing instruments for spectroscopic analysis

T. D. Morgan and F. W. Crawford, September 1944

Chemical plants depend on rapid analytical methods as a guide to keep the plant onstream. Successful applications of spectroscopic methods to these analytical problems have shortened the time interval from sampling to completion of an analysis, saving a significant amount of workers' time.

Characteristics of the differential-type flowmeter and conditions affecting its operation

L. K. Spink, November 1944

This work not only tells what to do and what to avoid in considering flowmeter applications, but also cites the penalties in terms of percent error if certain rules are not observed.

Plastics from petroleum

B. H. Weil, January 1945

This article provides a look at the many types of plastics that are produced from petroleum oil. The article includes sections on terminology, history, raw materials and processing routes to produce plastics. From the article's introduction:

"Plastics today, are materials with which to conjure. Industrial designers have depicted sleek plastic-bodied cars with transparent plastic tops and windshields. Advertisements have shown the home of the future as a dwelling built of plastic-bonded plywood, replete with plastic equipment from bathtub to lighting. Newspaper accounts have dwelled upon the coming age of plastics in which almost every article of commerce will have plastics used in them. All this publicity has served to focus the spotlight of attention upon materials and products which, in appearance and use, have long been of interest and utility to the public and industry alike."

Fuels for high-speed diesel engines

V. A. Kalichevsky, April 1945

The original development of trucks and busses as an important transportation factor was based on the use of gasoline engines to supply motive power. This source of power has continued predominantly because availability of gasoline has kept pace with demand. However, a considerable amount of work has been carried out, leading towards the development of diesel engines on the basic presumption that they are less discriminating with respect to fuels.

Super compressibility of natural gas upon compressor performance

R. S. Ridgway, May 1945

There seems to be some tendency to ignore the effect of super compressibility upon compressor performance and to assume that discrepancies from this source can be neglected. It is the aim of this paper to point out the dangers of such a practice, to indicate the practical value of the proper treatment and to present the methods of calculation which recognize this effect.

The fluid catalytic cracking process—How it operates

May 1945

This article provides a step-by-step look at the fluid catalytic cracking process, including a colored diagram provided by the M. W. Kellogg Co.

Functions and fundamentals of temperature in refinery process control

D. M. Boyd, September 1945

Instrumentation is the control of a product by its physical properties. At present, only two properties—temperature and pressure—are being extensively used in refining. It is evident that many additional properties can and should be used, such as refractive index, absorption spectra and dielectric property.

It is the purpose of this article to trace the development of temperature process control and to provide several examples of problems encountered in the design and operation of a 100-octane gasoline plant, which requires more than 300 instruments.

Synthetic lubricants from ethylene condensations

H. Schildwachter, March 1946

The condensation of ethylene with coal-tar fractions can produce valuable lubricants. The viscosity of such synthetic oils can be further increased by treatment with silent electric discharges. These oils show good stability under heat, are free of asphalt and potential sludge bodies, and do not form tars during oxidation at 120°C, among several other benefits.

Disposal of refinery wastes

L. C. Burroughs, July 1946

Since its inception, the petroleum industry has been confronted with the problem of the proper disposal of the wastes produced from oil-refining processes. Two conditions dictate close study on the subject of waste: the pressing necessity of more economical operation and the fact that political bodies continue to demand more from industry in the protection of both surface and underground water supplies.

Design of instrument-air-supply system for the process industry

W. C. Ludi, October 1946

The purpose of this article is to outline present practice in the design of instrument-air-supply systems for process units. These systems are important in plants using automatic control instruments since continuous satisfactory performance is essential to the production of specification products and the maintenance of operator morale. Also included is a discussion of instrumentation air drying methods and systems, and notes on the principal design features desired in the mechanical equipment of instrument-air systems.

Fundamental requirements for safe arrangement of drains and vents

J. H. Johnson, June 1947

The primary functions of drain and vent systems on oil processing units are to provide a means of quickly and safely disposing of oil and gas in an emergency, and to provide a means for safely draining and venting various parts of a unit during operation. The article details the fundamentals of arranging drains and vents in a processing unit.

Maintenance of tubular heat exchangers

J. G. Housman, July 1947

The proper techniques regarding maintenance on tubular heat exchangers at Standard Oil Co.'s Whiting refinery are discussed.

Cracking sulfur stocks with natural catalyst

R. C. Davidson, September 1947

This article presents the characteristics of catalyst which have been poisoned by sulfur and the procedure prohibiting the decline in activity caused by cracking gasoils containing relatively large amounts of sulfur compounds.

Refinery building program is stupendous

L. J. Logan, October 1947

Facing a substantial increase in the demand for petroleum products over the new few years, the refining branch of the petroleum industry is confronted with the necessity for a refinery building program beyond any figure heretofore quoted.

Where does the sulfur go?

M. J. Fowle and R. D. Bent, November 1947

This paper presents the distribution of sulfur in products when processing sour crude by distillation, thermal viscosity, breaking, gasoil cracking and reforming; catalytic cracking; catalytic desulfurization; and chemical treating.

Flange design calculations

H. E. Lonngren, November 1947

The author presents new formulas for determining the flange thickness quickly, with an assurance of obtaining a predetermined and uniform stress distribution in the flange. The derivation of the new formulas is based on the present formulas in the ASME and ASME-API codes.

The aromatic adsorption index as a rapid method for approximating catalyst activity

W. W. Scheumann and A. R. Rescorla, December 1947

Control of catalytic cracking operations requires frequent measurement of catalyst activity. The aromatic adsorption index is based on the ability of a cracking catalyst selectively to adsorb aromatic hydrocarbon from a hydrocarbon mixture.

Straight-line chart determination of absorber extraction efficiency

E. W. Ragatz, February 1948

The recently proposed straight-line chart method of absorber analysis has been broadened and refined with the resultant development of a highly significant overall performance factor. This factor has been given the designation of Extraction Efficiency and expresses the ratio (in terms of percent) of the theoretical minimum to actual lean oil rate required to affect a 95% butane recovery at any absorber operation. Application of this factor to a wide range of commercial units indicates the possibility of markedly improving the effectiveness of present day high-pressure absorbers.

New weapon of science—Radioactive isotopes

May 1948

A research project to unlock the still unknown secrets that make the conversion of coal and natural gas into gasoline possible is underway by Gulf Oil Corp. Radioactive isotopes are being applied to the study since the basic nature of the chemical reaction of the process remains a mystery. Sufficient technical knowledge exists to proceed with commercial production; however, the ultimate possibilities of the reaction cannot be judged until what happens in the reaction is better understood.

By sampling the presence of radioactive atoms in various stages of the process by a Geiger counter, the researchers hope to trace the course of carbon atoms and blueprint the entire reaction.

Industrial engineering in refinery maintenance planning

W. H. Reynolds, August 1948

The intention of this article is to emphasize the importance of providing basic tools for the analysis and investigation of all plant procedures. A "job order" system with resultant cost segregation and accumulation is offered as a basis for improving plant routines.

Designing for efficiency—Gas compressor systems

T. G. Hicks, December 1948

Gas compression plays a necessary part in operations throughout the refining, natural gasoline and petrochemical processing plants. Whether the gas handled is from a field vacuum gathering system, is being moved through a long-distance pipeline or is evolved from a conversion reaction in a processing facility, the problems of compressor installation and station design are much the same. Certain utilities must be provided, piping must be worked out to accommodate the process operating conditions, adequate foundations must be designed and maintenance requirements must be considered, among other factors.

Nuclear fission as a source of competitive energy

T. R. Hogness, April 1949

Currently, there is no such thing as atomic power, in the sense of the strict definition of power. However, surely, we shall have this power and in the not too distant future. The principles are known, tentative designs for power reactors have been made, and many necessary preliminary experiments are under way. With our faith in the ability to solve a very difficult problem, feasibility is fast growing into certainty.

Analytical instruments in automatic control systems

N. Gildersleeve, June 1949

There is a significant trend in process plant instrumentation toward the more general use of analysis-type instruments for the direct control of operating variables. The development of satisfactory instrumentation for the automatic control of the physical variables—temperature, pressure, flow, liquid level, etc.—resulted in great improvement in process plant operation, so now instruments capable of analyzing process stream compositions will bring about smoother operation of process equipment and a higher percentage of on-specification production.

Drainage time for bubble cap columns

J. L. Huitt, W. C. Ziegenhain, F. C. Fowler and R. L. Huntington, November 1949

The time required for a fractionating column to drain after it has been taken offline is a factor that enters the routine operation of many plants employing distillation. However, literature reports little, if any, experimental data on this operation and no method of calculating this drainage time. This article addresses this challenge.

Power plants for modern refineries

T. G. Hicks, December 1949

Power plants serving today's refining, natural gasoline and petrochemical plants have come a long way since the well-known oil field boiler days. No longer is steam generation the only function of the refinery power plant. Electricity in large quantities becomes more necessary every time a new production operation is introduced. With the decrease in availability of byproduct fuels, refinery power plant efficiency takes on a new importance. To achieve low cost production, today's refinery designer must strive for the optimum balance obtainable between process and power generating facilities. Obtaining such a balance is not readily done because it involves a multitude of factors. HP

LEE NICHOLS, VP, Content/Editor-in-Chief

The 1950s: Capacity expansion, HDPE/PP, polycarbonate, computers and rocket science

The 1950s marked an evolution in the use of oil by nations around the world. The processing of crude oil into fuels (e.g., gasoline and aviation gasoline) was imperative for economies to function—the use of oil increased significantly in many countries' total energy mix. For example, the use of oil was imperative during reconstruction efforts in Western Europe post World War 2 (WW2). Petroleum products in Europe's total energy mix increased from 10% at the end of WW2 to 21% in the mid-1950s and upwards to 45% in the 1960s.[68]

Across the world, nations were investing in new refining capacity to satisfy demand for refined fuels. One of the first refineries to startup post WW2 was the Ras Tanura refinery in Saudi Arabia—the refinery began operations approximately 1 mos (October 1945) after the end of the global conflict. By the early 1960s, the Ras Tanura refinery expanded production capacity from 50,000 bpd to 210,000 bpd.[69] Additional refining capacity increased in other nations and regions, including India, southeast Asia, the U.S., Western Europe and the first refineries in Africa—two refineries were built in Algiers, Algeria and Durban, South Africa in 1954, followed by refinery construction in Angola, Ghana, Nigeria and Senegal in the late 1950s/early 1960s.[70]

The 1950s was also a time of new technological discoveries for the refining and petrochemical industries. These included new refining and petrochemical processes to produce higher octane fuels, new derivatives of polyethylene (PE), the evolution of catalyst design, new chemical products, the adoption of computers in plant operations and the advancement of rocket fuels technology.

FIG. 1. Phillips Research Complex. The inset shows the site of the development of PP. Photo courtesy of American Chemical Society and Phillips 66 (successor of Phillips Petroleum Co.).

Catalytic research and development advances. After WW2, demand for high-octane gasoline increased globally—fluid catalytic cracking (FCC) capacity witnessed a significant capacity buildout in the 1940s to produce high-octane fuels for the Allied war effort. In turn, researchers developed new technologies to advance refining processes to produce higher octane fuels. For example, the U.S. added approximately 4 MMbpd of octane improvement capacity (e.g., catalytic reforming, isomerization, alkylation, hydrotreating)—directly or indirectly—during the 1950s.[71] Another process—Platforming, invented in the late 1940s by Vladimir Haensel of UOP—was instrumental in the eventual removal of lead from gasoline. The process also used a platinum catalyst to produce gasoline with a higher octane rating, an unconventional approach at the time due to the high costs of precious metals. Around the same time, hydrodesulfurization was commercialized. Today, most refineries have one or more desulfurization units.

In the 1950s, FCC processing technology started to incorporate zeolite catalysts in the reaction. Due to their molecular structure, zeolite catalysts are extremely effective in the reaction process—they have higher performance at lower pressures. In the early 1960s, the effectiveness of zeolite catalysts was also instrumental in making the hydrocracking process economical—the modern hydrocracking process was developed at Standard Oil of California's (now Chevron) Richmond

refinery in 1959; the refinery also installed the first paraxylene unit in the U.S. in 1954. Within 10 yr, global hydrocracking capacity increased by a factor of 1,000, reaching approximately 1 MMbpd.[72]

High-density polyethylene, polypropylene and Ziegler-Natta. In 1951, J. Paul Hogan and Robert L. Banks were conducting catalyst research at Phillips Petroleum Co.'s research complex (**FIG. 1**) in Bartlesville, Oklahoma (U.S.). According to literature[73], they set up an experiment using a nickel oxide catalyst but included small amounts of chromium oxide. In addition, they fed propylene, along with a propane carrier, into a pipe packed with catalyst. The result was that the chromium had produced a white, solid material. The two chemists had produced a new polymer: crystalline polypropylene (PP).[73]

While using the same chromium catalyst, Hogan and Banks conducted research to produce a new ethylene polymer. Within a year, the two chemists discovered a new process that used far less pressure than the PE process invented by Imperial Chemical Industries in England. **Note:** The History of the HPI segment of the 1930s provided a detailed history of the discovery of PE. Hogan and Banks' process required only a few hundred pounds per square inch (psi) vs. the PE process that required 20,000 psi–30,000 psi.[73] The new process produced a high-density polyethylene (HDPE). The discovery of HDPE and PP launched the Phillips Petroleum Co. into the global plastics market. The company marketed their new discovery under the name Marlex. The new polyolefin product line became immensely popular as the basis for a toy developed by Wham-O. The toy maker used Marlex to produce a round plastic tube they sold under the name Hula Hoop.[74]

Around the same timeframe, more than 4,700 mi from the Bartlesville research lab, German chemist Karl Ziegler was experimenting with ethylene at the Max Planck Institute for Coal Research in Germany. Ziegler's goal was to synthesize PE of a high molecular weight. However, each reaction was unsuccessful due to contamination of nickel salt.[75] After testing several different metals to counteract nickel salt contamination, he discovered titanium-based catalyst was immensely successful at accelerating the reaction process. Ziegler's discovery led to a new process to produce PE without using high pressure and temperature. He also discovered that the produced PE consisted of very ordered, very long, straight-chain molecules (**FIG. 2**).[76]

Italian chemist Giulio Natta (**FIG. 3**) heard about Ziegler's discovery while working at the Italian chemical company Montecatini. After Montecatini purchased the commercial rights to Ziegler's new catalyst in Italy, Natta proceeded to conduct research on Ziegler's work, focusing not on ethylene like Ziegler but on propylene polymerization. Through these endeavors, Natta successfully produced isotactic PP, which Montecatini began to produce on a commercial scale in 1957. By x-ray investigations, Natta was also able to determine the exact arrangement of chains in the lattice of the new crystalline polymers he discovered.[77]

Ziegler and Natta's research and development on catalyst polymerization became known as Ziegler-Natta catalyst. For their work, both men were awarded the Nobel Prize in Chemistry in 1963. This catalyst is still in use today for polymer production.

Through the work of Hogan, Banks, Ziegler, Natta and other professionals aiding in the research and development of

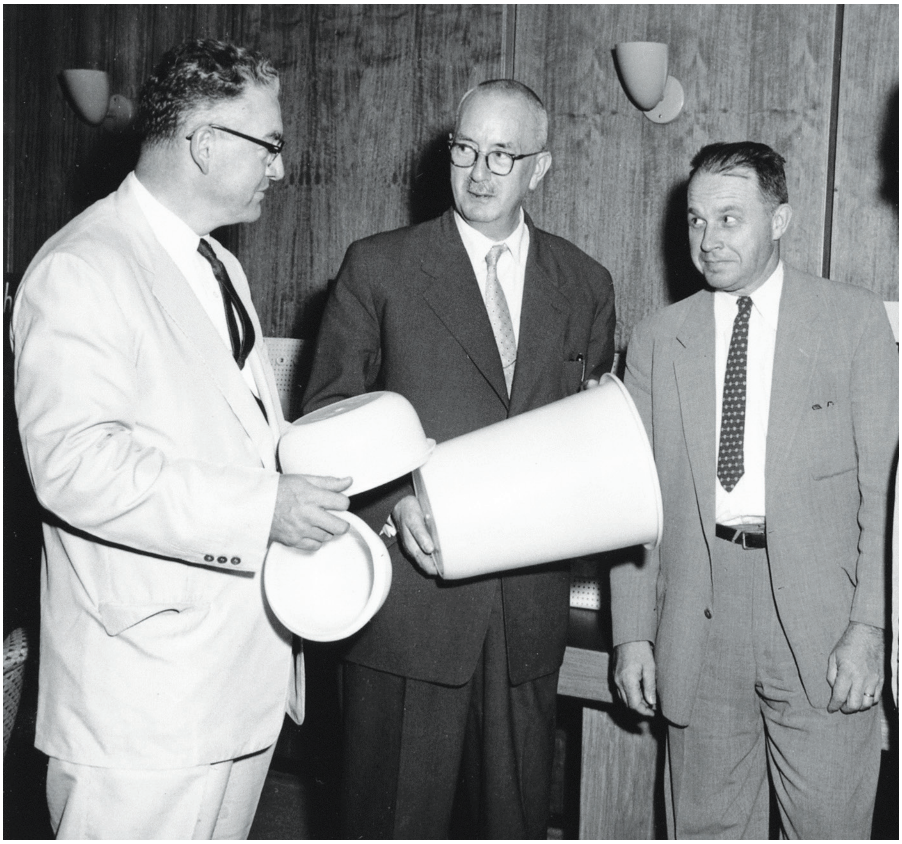

FIG. 2. Karl Ziegler (center) with members of the Hercules group that commercialized HDPE as Hi-fax. Photo courtesy of Hercules Inc. The company was acquired by Ashland Global Specialty Chemicals Inc. in 2008.

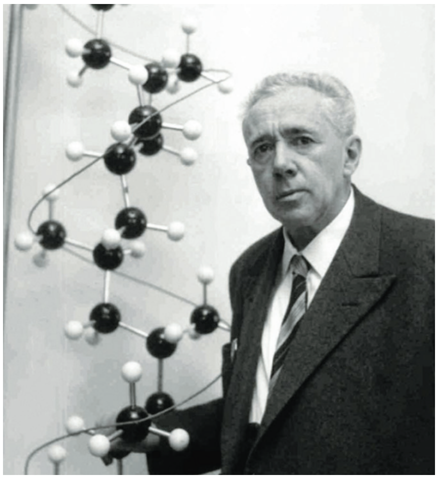

FIG. 3. Giulio Natta was awarded the Nobel Prize in Chemistry in 1963 for his work on propylene polymerization. He shared the prize with Karl Ziegler. Photo courtesy of Maire Tecnimont.

these chemists, HDPE and PP have produced new products used extensively in many different applications, raising the standard of living for people around the globe. Since being discovered in the 1950s, both PP and HDPE have witnessed their market value surge over the past 70 yr, eclipsing $100 B and $70 B, respectively.

Commercialization of polycarbonate and emulsion technology. Although first discovered in the late 1890s, polycarbonate did not find commercial use until the late 1950s. The polymer was first created by German chemist Alfred Einhorn while working at the University of Munich in 1898. Dr. Einhorn is best known for synthesizing the local anesthetic procaine, which became known as Novocain, a numbing agent primarily used in dental procedures—prior to his discovery, cocaine was a commonly used local anesthetic which had undesirable side effects, including toxicity and addiction.[78,79] According to literature, Dr. Einhorn was attempting to synthesize cyclic carbonates and produced polycarbonate by reacting hydroquinone with phosgene.[78] However, no commercial use was found for this material.

Approximately 30 yr later, Wallace Carothers and his research team at DuPont created polycarbonates while working on the development of polyesters and nylon. An account of these discoveries—polyesters and nylon 66—are detailed in the 1930s segment. However, Carothers' team did not find a commercial use for the produced polycarbonates.

In 1953, a commercial use for polycarbonates was discovered almost simultaneously in two different parts of the world—this year also marked the first iteration of the Petrochemicals Process Handbook (published in the November issue of *Petroleum Refiner*, the forerunner to *Hydrocarbon Processing*), which detailed emerging petrochemical processes. While researching polycarbonates at Bayer's (the company's Material Science division became Covestro in 2015) research and development laboratories in Uerdingen, Germany, Dr. Herman Schnell created the first linear polycarbonate.[80] Approximately 1 wk later, Dr. Daniel Fox also discovered the same compound while conducting research on new wire-insulating material at General Electric (GE) in Schenectady, New York (U.S.).[81] Both Schnell's and Fox's polymer were chemically the same but differed structurally—i.e., Schnell's polymer was a linear polycarbonate and Fox's polymer was a branched material.[78,81]

Both Bayer and GE filed for U.S. patents in 1955, leading to legal challenges on the rightful owner of the technology. Bayer was awarded the patent; however, the two companies agreed that the patent holder would grant a license for an appropriate royalty. This agreement allowed both companies to develop and market their own polycarbonate technology.[82] Bayer began marketing their product in 1958 under the trade name Makrolon. GE began commercial production in 1960 and marketed their product under the name Lexan—the GE Plastics division was created in 1973, later being acquired by the Saudi Arabian chemical company Saudi Basic Industries Corp. (SABIC) in 2007; SABIC divested the subsidiary (known as the Polymershapes business) in 2016.[83]

Over the next nearly 70 yr, polycarbonate has evolved and is used in a multitude of products for everyday life. The tough plastic is used in many applications that require transparency and high impact resistance. These include in the production of windows, protective eye wear, electronic components (e.g., electrical and telecommunications hardware), construction materials, materials within the automotive and aviation industries, and other niche market applications.[81]

The late 1940s/early 1950s also witnessed the advancement of acrylic emulsion technology. The technology

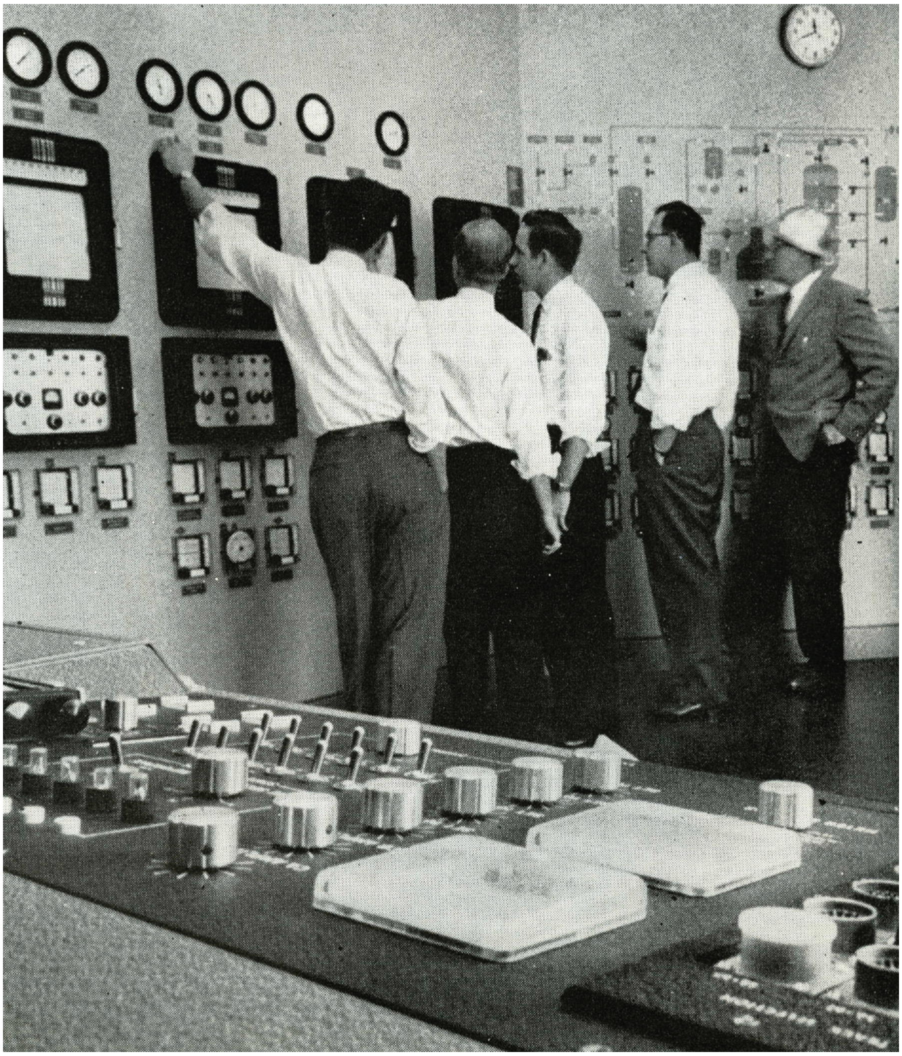

FIG. 4. The RW-300 computer system, foreground, was used to enhance operations at Texaco's Port Arthur refinery's 1,600-bpd polymerization plant. In the background, Texaco engineers and TRW personnel check control charts. Photo courtesy of *Business Week.*

was invented by scientists at Röhm and Hass—the company, founded in Esslingen, Germany by Dr. Otto Röhm and Otto Haas in 1907, invented Plexiglas (this discovery was detailed in 1930s installment).

To find a new product to market, the company's research department, led by Harry Neher, conducted experiments on acrylic monomer synthesis. The research built on earlier work by I. G. Farben (German chemical and pharmaceutical conglomerate) scientist Walter Reppe. After modifications, Neher invented a new semi-catalytic process called the F Process, which resulted in the production of vast qualities of cheap acylate monomers.[84] However, the company did not know exactly what to do with their newfound discovery.

One idea came from two scientists at the company, Benjamin Kline and Gerald Brown. They suggested the aqueous emulsion technology could make a great house paint.[84] At the time, most paints were solvent paints; however, they emitted an odor, were toxic and flammable, and hard to clean up. In 1951, Röhm and Hass built an F Process plant in Houston, Texas (U.S.) and produced their first paint emulsion product in 1952—it was named Rhoplex AC-33. The product had several benefits vs. solvent-based paints: it had a low odor, was easy to clean up, had a resistance to cracking and was environmentally friendly.

Röhm and Hass perfected the product over the next two decades, introducing a range of exterior and interior paint products with different finishes (e.g., flat, semi-gloss and gloss). By the early 1970s, Rhoplex AC-33 surpassed Plexiglas sales for the company and created a new line of acrylic paints to rival solvent-based paints.

FIG. 5. Goddard standing next to his rocket. On March 16, 1926, he successfully launched the world's first liquid-propellant rocket. Photo courtesy of the U.S. Smithsonian National Air and Space Museum.

Closing the loop: The computer-integrated manufacturing era begins. On April 4, 1959, Texaco started operations on the first direct digital control computer at a refinery. The system—a Thompson Ramo Wooldridge (TRW) RW-300 computer—was installed on the company's 1,600-bpd polymerization unit at the Port Arthur refinery (Texas, U.S.). The initiation of this system "closed the loop" in the first fully automatic, computer-controlled industrial process.[85]

The installation of the system began several years before startup. TRW and Texaco engineers worked for more than 2.5 yr on a feasibility study for converting the plant to full automation. The 318-pg report provided robust detail on all actions the system would have to monitor. This analysis provided a basis for Texaco engineers to design the instrumentation and control system for the unit.[86] The initial goal of the computer system—which totaled approximately $300,000 (computer, instrumentation, labor and other equipment),[86] nearly $2.9 MM today after adjusting for inflation—was to raise the plant's efficiency by 6%–10%.

The work of the computer was described succinctly by Texaco's Chief Process Engineer, Charles Richker. "It gets an analysis of incoming gas and outgoing gas; it senses and measures pressure, flows and temperatures; it calculates catalyst activity; then it weighs all these together and decides what the processing unit should do to get the most product for the least cost," said Richker. "Finally, it sets the controls and rechecks its figuring."[86] The computer accomplished these tasks in a matter of seconds.

The RW-300 computer was able to accomplish more measurements, faster than refining personnel could ever hope to achieve. From literature, for example, the computer could read dozens of recorder-controllers that indicated pressure, temperature and flow, and then relate the readings that indicated the level of activity of the reaction or condition of the catalyst. The computer could then calculate the complex interrelationships of the process, all in time to reset the controls to keep the plant operating at maxi-

mum efficiency. The computer could conduct these readings every 5 min, 24 hr a day (**FIG. 4**).[86]

The success of the computer system led to the adoption of numerous installations over the next several years. The second RW-300 computer for the processing industry was installed at Monsanto's Chocolate Bayou, Texas (U.S.) petrochemical plant in 1960, followed by B. F. Goodrich's chemical plant in Calvert City, Kentucky (U.S.). Several other installations of the RW-300 occurred in the early 1960s, including at BASF's plant in Ludwigshafen, Germany; Gulf Oil Co.'s catalytic cracking plant in Philadelphia, Pennsylvania (U.S.); Petroleum Chemicals' ethylene plant in Lake Charles, Louisiana (U.S.); among others.[87]

IBM introduced its first multi-purpose industrial control system—the IBM 1710—in March 1961. The computer—which cost $111,000–$135,000 ($1 MM–$1.27 MM today after adjusting for inflation)—was used for a variety of sampling and the interpretation of data in the processing and manufacturing industries, including quality control, industrial process study and process optimization.[88] The system was first installed at American Oil's Whiting refinery in Indiana (U.S.) in 1961, followed by additional installations at Standard Oil of California's El Segundo refinery in Richmond, California (U.S.) and DuPont's acrylonitrile pilot plant in Gibbstown, New Jersey (U.S.) in the same year.[86,87]

From the late 1950s to the early 1960s, more than 40 computer control systems were installed in the chemical and petroleum sectors.[87] Although initially expensive, the use of computer systems revolutionized hydrocarbon processing operations and provided significant benefits to operating personnel and plant production. This period—later known as the computer-integrated manufacturing era for the hydrocarbon processing industry—transitioned the refining and chemical industries into a new computer age. Computer systems would continue to evolve over the next several decades, providing new enhancements and benefits along the way.

Rocket designs/fuels evolve, and the space race begins. Production of various fuels and gases have been instrumental in the development of space exploration and satellite technologies, especially in the construction of artificial satellites (e.g., Kevlar, invented in the 1960s by DuPont, help protect satellites in orbit from the harsh conditions of space) and propulsion. Although the origins of rocket propulsion go back several centuries (the Chinese used tubes filled with gunpowder—called "arrows of flying fire"—to repel the Mongols during the battle of Kai-Keng in 1232),[89] modern rocket propellant technology traces its roots to the mid-1900s.

The era of modern rocketry began with theories derived from the Russian rocket scientist Konstantin Tsiolkovsky. His work *Exploration of Outer Space by Means of Rocket Devices*—published in 1903—put forth the idea of both utilizing rockets for space flight and using liquid propellant for rocket propulsion.[90] These ideas and his research on the subject inspired future scientists that would revolutionize rocket fuel development over the next several decades. For this, Tsiolkovsky is known as the father of modern astronautics.

The first successful liquid-fueled rocket test was conducted in 1926 by Robert Goddard. Throughout his research, Goddard discovered that using liquid fuel provided more acceleration vs. other forms of propulsion, such as gunpowder. His rocket design had the combustion chamber and nozzle at the top of a frame made up of two vertical tubes, which would then carry the liquid fuel (comprised of liquid oxygen and gasoline) from the tanks at the bottom to ignite the rocket.[91,92]

On March 16, 1926, in Auburn, Massachusetts (U.S.), Goddard's rocket blasted off the launchpad. The rocket flew for 2.5 sec and reached an altitude of 41 ft.[91] The launch proved that liquid fuels could be used to propel rockets, setting the stage for the evolution of rocket engine designs, which would eventually lead to the use of satellites and space exploration.

Although Goddard's discovery was revolutionary, he kept his findings mostly secret. His work was barely known until the U.S. Smithsonian published his theory *A Method of Reaching Extreme Altitudes.* However, several media outlets openly mocked his theories. For example, the *New York Times* dismissed Goddard's theories as lacking basic knowledge learned in high schools—the publication printed a correction in July 1969 as the Apollo 11 mission launched on its historic mission to the moon.[91]

In the late 1920s, the world's first large-scale experimental rocket program began under the leadership of the German rocket technology pioneer Fritz von Opel (nicknamed Rocket Fritz) and other associates, including Max Valier, who was one of the founders of the German Spaceflight Society (Verein für Raumschiffahrt).[93] The Opel RAK significantly advanced rocket and aviation technology, especially in propulsion. In 1928, the group developed its first liquid-fueled rocket, which used benzol—a coal-tar product consisting mainly of benzene and toluene—as fuel and nitrogen tetroxide as the oxidizer.[93]

The research and testing completed on Opel RAK led to the development of Germany's V-2 rocket, the world's first long-range guided ballistic missile powered by a liquid-propellant (liquid oxygen and ethyl alcohol) rocket engine. After WW2, several nations used the V-2 rocket technology to develop their own military missile programs, as well as advance space exploration. These initiatives were supported by hydrocarbon processing companies. For example, Air Products was commissioned by the U.S. to build plants that could supply large quantities of liquid oxygen and nitrogen to support the country's emerging missile and space program.[94] After Russia successfully launched Sputnik into space in 1957 (the satellite used kerosene T-1 as a fuel and liquid oxygen as an oxidizer[95]), Air Products was awarded a contract to supply liquid hydrogen to the U.S. Air Force—and later to NASA—to advance the country's rocket technology to compete against the Soviets during the Cold War and space race. The U.S. eventually created Rocket Propellant-1, which is a highly refined form of kerosene and liquid oxygen.

These fuels aided the advancement of rocket technology, leading humans to break the boundaries of space and place satellites into geosynchronous orbit, significantly evolving the way the world communicates, navigates and explores not only Earth but the distant cosmos. These advancements would not have been possible without the fuels and products produced from the hydrocarbon processing sector. HP

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LEE NICHOLS, VP, Content/Editor-in-Chief

Excerpts from the 1950s: Capacity expands after WW2 and technologies and maintenance mature

The following is a mixture of technical articles, columns and headlines published in the 1950s by *Petroleum Refiner,* the forerunner to *Hydrocarbon Processing.* This collection of excerpts provides a look into the major technological advancements and topics/trends in the hydrocarbon processing industry during that timeframe.

First postwar cargo of crude for rebuilt Dunkirk refinery received

February 1950

Progress in new British refinery

E. N. Tiratsoo, February 1950

The first unit of the Shell Oil Co. refinery near Stanlow has been completed and is in operation using crude oils from the Middle East.

Propylene, a valuable feedstock for alkylation

E. C. Oden, W. J. Burch and G. R. Jones, March 1950

Alkylates produced in refinery alkylation processes have high octane numbers, lead susceptibilities and heat values and boil in the gasoline range to rank among the most important components of aviation and motor gasolines. The reaction most widely used in the process has been the combination of isobutane and butylene.

This article provides data from the operation of a sulfuric acid alkylation unit, on propylene, and shows the effect of the major operating variables on aviation alkylate quality, alkylate yield and acid consumption.

The new metals—Molybdenum, titanium and zirconium

May 1950

Techniques for producing and fabricating these new metals are progressing rapidly, so that within the next few years, they should take an important place in industry, along with the other special metals such as stainless steel, super alloys, tantalum and others.

Pemex's Salamanca refinery is nearing completion

June 1950

The new $12-MM plant will help the geographical balance of Mexico's refining and marketing area by providing a 60% increase in refining capacity in the country.

Corrosion-resistant liners in refinery vessels

G. C. Carpenter, July 1950

The internal protection of refinery process vessels becomes increasingly important as throughputs are increased and crude oils become less sweet and saltier.

Bubble tray design and layout—Parts 1 and 2

J. A. Davies, August and September 1950

The bubble tray is possibly the most important single item of equipment used in petroleum processing plants. Despite the use of tens of thousands of these trays, both their initial design and their performance in operation present certain mysteries to engineers and operators alike.

In this series of articles, the author has organized the complete tray calculation problem into an orderly routine. He has attempted to provide sufficient information in practice, theory and procedure to allow a person without considerable experience to reach sound answers on bubble tray problems. Part 1 deals with the mechanical details of the bubble tray, while Part 2 covers the actual calculation of tray performance.

Work progresses on Europe's largest oil refinery

December 1950

Anglo-American Oil Co.'s $100-MM, 5-MMtpy refinery is nearly completed. The plant is being built in Fawley, Hampshire, England, approximately 15 mi southeast of Southhampton. Once completed, the facility will produce 42,500 bpd of crude naphtha and white spirit, 6,000 bpd of kerosene, 14,000 bpd of diesel fuels and gasoils, 6,000 bpd of light fuel oils, 30,000 bpd of bunker fuel and 3,500 bpd of asphalts.

Tuning automatic control systems

J. L. Serrill and L. E. Jewett, January 1951

This article describes a method by which plant instrument adjustments can be made in orderly sequence to attain optimum overall behavior of process units.

Maintenance facilities in gasoline cycling plants

H. Givens, April 1951

Downtime is a constant threat to even well-managed plants. However, carefully planning repair procedures can significantly mitigate such problems.

The petrochemical engineer looks at rocket fuels

M. Sittig, May 1951

The rocket-type aircraft engine appears to be susceptible to improvements in performance because of fuel development,

which can be expected to exceed those which have occurred with the piston-type aircraft engine.

In view of this, the petrochemical engineer should possess some knowledge of those materials currently in use as rocket fuels and of those materials which are potentially attractive as tomorrow's propellants.

The middle of the barrel comes of age

A. L. Nickerson, July 1951

There is an increasing need to shift oil refining operations from the emphasis on gasoline production to increasing the yield of middle distillates.

Refinery painting

W. B. Cook, March 1952

One of the most troublesome problems at every refinery is that of minimizing external corrosion. Gulf Coast refiners have developed a progressive program of corrosion control through systematic refinery painting.

In this article, the author discusses the many problems of surface protection through painting. Factors to be considered include the nature of the surface to be protected, the character of the exposure expected and the various paint materials available for protection.

Production of high-purity aromatics for chemicals

D. Read, May 1952

A combination of Platforming and Udex extraction provides the refiner with a tool for manufacturing high-purity aromatics.

Improved process polymerizes olefins for high-quality gasoline

G. E. Langlois and J. E. Walkey, August 1952

This article details an improved catalytic polymerization process is being licensed to produce high-quality gasoline from light olefins. The polymer is a 98-octane gasoline.

Techniques for cat unit turnarounds

J. G. Traxler and K. T. Beavers, February 1953

This article presents the complete details on how to conduct a turnaround, including a description on worker coordination.

Shale oil—What is it?

G. U. Dinneen, February 1954

This work provides analyses of 10 U.S. and 10 foreign shale oils yield in comparison with crude petroleum.

A look ahead in vessel design

E. W. Jacobson, November 1954

Lower initial cost and longer trouble-free life of pressure vessels are dependent on a better understanding of corrosion, brittle fraction, creep at high temperatures, graphitization and hydrogen penetration, among other items.

World demand expands faster
R. S. Spann, January 1955

Global petroleum demand is expected to reach more than 14 MMbpd in 1955, an increase of about 6.6% vs. 1954.

Turnaround scheduling
J. O. Thoen, March 1955

Allowable run length, worker availability and process commitments all play major roles in turnaround scheduling.

Carbon formation in cat cracking
P. B. Crawford and W. A. Cunningham, January 1956

This article details a method to estimate the effect of charging rate, process period and temperature on the quantity of carbon deposited on the catalyst in a catalytic cracking unit. In addition, a path is provided to use fixed-bed reactor data for estimating results with the same catalyst and charge in moving bed or turbulent fluidized reactors.

What causes hydrogen attack?
G. R. King, March 1956

Hydrogen attack takes many forms. Some of these are more serious than others. This article will help plant personnel recognize the various forms of hydrogen attack and plan the most economical maintenance program.

How to select the right pump motor
October 1956

Do you know when to use the normal inrush and when to use the low inrush motor? This comparison between speed-torque characteristics of pump and motor will help you decide.

Is your distillation column in balance?
W. D. Harbert, November 1956

The operation of a distillation column is more costly if it is not in balance. This article provides a non-mathematical discussion of column balance and how to achieve it.

Analog computers calculate heat transfer
R. S. Schechter, February 1957

The increased availability of computing devices has caused considerable interest in expanding the scope of problems which are adaptable to automatic computation. The purpose of this article is to point out the usefulness of the analog computer in solution of natural convection problems.

Future fields of elastomers
J. Bjorksten, March 1957

The outlook for elastomers is exceptionally bright because of low fabrication costs.

Here is data on propane fractionation
E. E. Smith and C. E. Fleming, July 1957

Some of the advantages of separating hydrocarbons according to their solubility in liquid propane are discussed in this article. These data are compared with separation by distillation.

What to do about corroding isomerization units
J. F. Mason and C. M. Schillmoller, July 1958

Even though the process aspects of butane isomerization have been discussed in several articles in recent years, little has been said about the corrosion problems associate with these units. The intention of this article is to review some of these problems and point out where corrosion has occurred or can normally be expected to occur, so that this information may serve as a guide to those who have butane isomerization units in the design or planning stage.

Urea—The petrochemical to watch
L. F. Hatch, August 1958

Urea is one of the fastest growing petrochemicals, with a 270% production increase in 8 yr. It is a triple-threat petrochemical with a dynamic future for fertilizer, animal feeds and synthetic resins.

Alkylation—What you should know about this process
R. E. Payne, September 1958

This comprehensive article tells of the many factors that influenced the alkylation process and its products. It will focus on the commercial aspects of alkylation—plant designs, operating techniques and process variables. The article will also provide details regarding investment and operating costs, some octane blending data and process history.

A checklist for plant layout
J. F. McGarry, October 1958

Whether it is a refinery or petrochemical plant, the article provides tips that will help attain maximum flexibility and compactness at a reasonable initial cost.

Petroleum Refiner: The Oil Centennial Issue
January 1959

This issue of the *Petroleum Refiner* provided a detailed look at the past 100 yr of the oil industry. This included the history of refining and petrochemical discoveries and technologies, as well as a look at the current global demand for petroleum products.

Find the best air fin cooler design
E. U. Nakayama, April 1959

Plant personnel must compare investment costs with operating costs to come up with the best cooler design. This article provides a sample problem that details this notion in action.

Which acetylene removal scheme is better?
W. H. Stanton, May 1959

Which method of acetylene removal—absorption or hydrogenation—is the most economical? One method is economically superior to the other depending upon the following variables: plant size, byproduct value of acetylene and acetylene made per 100 lbs of ethylene produced. This article provides the economics of absorption vs. hydrogenation for removing acetylene from rich ethylene streams. HP

LEE NICHOLS, VP, Content/Editor-in-Chief

The 1960s: Synthetic oils, zeolite catalysts, LLDPE, OPEC and and creation of the PLC

During the 1960s, the global refining and petrochemical industries witnessed new processes and products that enhanced the daily lives of millions of people around the world. The decade was responsible for the creation of new petrochemical products to provide better and more durable goods within many industrial sectors and consumer goods applications. Other innovations, such as the creation of synthetic oils and synthetic zeolite catalyst, enhanced processing operations and engine/fuel performance in the automobile and aviation sectors. The 1960s was also a prominent decade for LNG trade [the first transatlantic LNG cargo was carried on the *Methane Pioneer* in early 1959 from Constock's LNG production facility in Louisiana (U.S.) to the UK; the UK also received the world's first commercial LNG cargo from Shell's *Methane Pioneer* vessel in October 1964 from Algeria; LNG exports from Alaska (U.S.) to Japan commenced in the late 1960s],[96] the creation of the programmable logic controller (PLC)—a significant evolution in automation—and the creation of the Organization of Petroleum Exporting Countries (OPEC), which was, and still is, a major force in setting global oil prices.

Creation and widespread adoption of synthetic oils. Although the first synthetic hydrocarbon oils were produced in 1877 by French chemist Charles Friedel and American chemist James Mason Crafts (i.e., Friedel-Crafts alkylation and acylation reactions), synthetic oils did not see widespread adoption until post-World War 2 (WW2).

Prior to WW2, several individuals developed new reactions to produce synthetic oils. These included German scientists Friedrich Bergius, Franz Fischer and Hans Tropsch (the Bergius and Fischer-Tropsch processes were detailed in the 1920s and 1940s history segments), as well as American researcher F. W. Sullivan while working at Standard Oil of Indiana (U.S.). Sullivan's team tried to commercialize synthetic oils in 1929; however, this attempt was challenged due to lack of demand. Regardless, Sullivan published a paper in 1931 titled "Synthetic lubricating oils relation between chemical constitution and physical properties," which, along with research from the German chemist Hermann Zorn, provided a foundation for the future widespread use of synthetic oils in the aviation and the automobile sectors—Zorn and his team researched more than 3,500 synthetic esters during the early 1940s to find an alternative to petroleum oil to help fuel Germany's war machine.[97,98]

The need for synthetic oils did not materialize until Germany's invasion of the Soviet Union during WW2. During the Battle of Stalingrad, the harsh Russian winter demobilized German tanks, fighter planes and other military vehicles. The main culprit: temperature. Conventional petroleum oil could not stand up to the frigid temperatures during the harsh Russian winter. These oils were produced through conventional distillation, which has several drawbacks, including solidifying in low temperatures, rendering its use extremely ineffective in extremely cold environments—conventional distillation could not completely remove impurities such as waxes, which would solidify in cold temperatures, leading to the inability of engines to start.[98] This event demonstrated that a new form of lubricating oil was needed.

The use of synthetic oils found its demand within aircraft engines during and post-WW2. While Zorn was conducting widescale tests on different synthetic esters in Germany, American chemist William Albert Zisman was researching synthetics at the Naval Research Laboratory in Washington D. C. (U.S.). His work (1942–1945)—detailed in the technical article "Synthetic lubricant fluids from branched-chain diesters physical and chemical properties of pure diesters,"[99]—led to the development of the first diester synthetic base oils, a precursor to the development of modern synthetic lubricants.[98,100] With the creation of the jet engine in the 1940s, synthetic oils were able to protect engine components against extreme temperatures during flight, a challenge that conventional oils could not accomplish. As a result, synthetic oils were used for military and commercial air travel.

It was not until the 1960s that the idea of using synthetic oils in the automo-

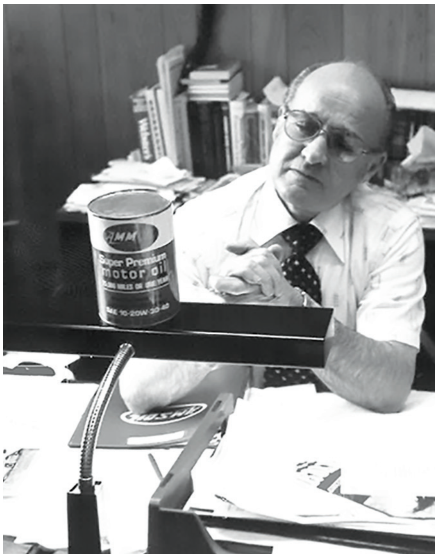

FIG. 1. Albert Amatuzio developed the world's first synthetic motor oil to meet API service requirements. For this, he is known as a pioneer in synthetic lubrication. Photo courtesy of AMSOIL.

bile industry could provide significant benefits to engine performance. American pilot and inventor Albert Amatuzio conducted research in the 1960s on the use of synthetic lubricants in automobile engines. As a squadron commander in the Minnesota Air National Guard and WW2 fighter pilot (he flew America's first operational fighter jet, the F80 Shooting Star),[101] Amatuzio was aware of the benefits synthetic lubricants provided aircraft engines. His goal was to find a way for automobile engines to gain the same lubricating benefits.

In 1966, Amatuzio formulated his first synthetic motor oil, testing it in his colleague's new 1966 Ford station wagon.[98] After the successful test, he continued to develop new synthetic oils and sell them throughout the late 1960s under the name AMSOIL. However, the public was slow to adopt Amatuzio's new synthetic motor oil despite the many benefits it provided vs. conventional lubricating oils. The primary challenge was price, as synthetic motor oil costs several times more than conventional motor oil.[98]

Seeking additional validation of performance standards established by the American Petroleum Institute (API) and the Society of Automotive Engineers, Amatuzio had his motor oil tested by a third-party laboratory in 1972. After rigorous tests, AMSOIL Synthetic Motor Oil became the world's first synthetic motor oil to meet API service requirements (**FIG. 1**).[98] This validation, along with major oil companies producing their own synthetic lubricating oils for the auto industry, would eventually lead to widespread adoption of synthetic motor oils for automobiles.

After Amatuzio's accreditation and continued sales of his novel product, Mobil followed suit, creating the first Mobil 1 fully synthetic motor oil in 1971—the company first introduced Mobilgrease 28 (still in use) in the early 1960s to prevent military plane wheel bearings from failing during landings in cold temperatures, followed by the Mobil-brand synthetic oil technology for big diesel engines powering oil drilling rigs on Alaska's North Slope (U.S.) in temperatures as low as –40°C in the late 1960s.[102]

FIG. 2. The delegation of Saudi Arabia at the historic Baghdad Conference in mid-September 1960. Photo courtesy of OPEC.

The formation of OPEC. Following WW2, global oil consumption began to expand significantly. During this timeframe, the U.S. was simultaneously the world's largest consumer and producer of oil, and global oil supplies were dominated by the Seven Sisters (five were headquartered in the U.S.)—Anglo-Iranian Oil Co. (now bp), Royal Dutch Shell, Standard Oil Co. of California (now Chevron), Gulf Oil and Texaco (both merged into Chevron), Standard Oil Co. of New Jersey and Standard Oil Co. of New York (both are now ExxonMobil). Up until the early 1970s, these multinational organizations controlled approximately 85% of the world's petroleum reserves—this included large oil reserves in the Middle East.[103]

Wanting to control more of its domestic reserves, several oil exporting countries—Iran, Iraq, Kuwait, Saudi Arabia and Venezuela—convened in Baghdad, Iraq in September 1960 (**FIG. 2**). This historic meeting's (the Baghdad Conference) goal was to discuss ways to increase crude oil pricing produced by these countries, as well as ways to respond to unilateral actions by the Seven Sisters and other multinational organizations.[103] This meeting led to the creation of the Organization of Petroleum Exporting Countries (OPEC), which witnessed its member countries increase over the next 15 yr.

OPEC grew in prominence during the 1970s, as its member countries gained greater control of their domestic production and began to play a greater role in world oil markets.[104] The organization still plays a decisive role in crude oil production, with the ability to significantly affect crude oil pricing globally.

During the 1960s, the Middle East also witnessed the expansion of regional refining and petrochemical capacity. For example, the Ras Tanura refinery in Saudi Arabia expanded its capacity from 50,000 bpd to 210,000 bpd.[69] Kuwait National Petroleum Co. expanded the Mina Abdullah refinery's capacity from 30,000 bpd to 145,000 bpd in 1963, as well as commissioned the 95,000-bpd Shuabia refinery in April 1968—the Shuabia refinery increased processing capacity to 195,000 bpd in 1975. The Shuabia refinery eventually closed in 2017; however, its infrastructure was incorporated into the country's capital-intensive Clean Fuels Project.[105] The Shuaiba Industrial Zone also housed Kuwait's first chemical fertilizer complex. Petrochemicals Industries Co.—established in 1963—commissioned the facility in 1967, which was the first of its kind in the Middle East. Saudi Arabia and Qatar followed suit, establishing the Saudi Arabian Fertilizer Co. in 1965 and the Qatar Fertilizer Co. in 1969.[106]

Synthetic zeolite catalysts are patented and commercialized. The term zeolite—microporous, aluminosilicate minerals—was first coined by Swedish mineralogist Axel Fredrik Cronstedt in 1756.[107] Cronstedt, who is most noted for discovering the elements nickel and scheelite (later to be known as tungsten), discovered zeolite after heating the mineral stillbite (tectosilicate minerals of the zeolite group) with a blowpipe flame. The process produced a large amount of steam from water that had been absorbed by the mineral.[107,108] After observing the reaction, Cronstedt coined the mineral "zeolite" from the Greek words "to boil" and "stone."[107]

Modern research and development of synthetic zeolites were pioneered by individuals such as New Zealand-born chemist Richard Barrer (his work in adsorption and synthesis began the era of synthetic zeolites); Robert Milton, Donald Breck and T. B. Reed at Union Carbide (their work during the late 1940s/early 1950s led to the discovery of synthetic zeolites A, X and Y); and Jule Rabo and Edith Flanigen who both worked with Milton's team at Union Carbide. Rabo led the catalyst research group at Union Carbide from 1957–1961 and played a key role in the discovery of the catalytically active ingredient used worldwide in the catalytic cracking of gasoils to produce gasoline.[109] Flanigen was instrumental in the development of zeolite Y. In his historical perspective on zeolite research, Milton described Flanigen as a world expert on zeolite synthesis and the first to synthesize high-silica Y with

silica/alumina rations above 4, the first to remove aluminum from zeolite lattices without loss of structure, and responsible for identifying and evaluating the myriad of samples from Union Carbide's investigation of sedimentary zeolite deposits in the Western U.S.[109] Dr. Flanigen's work is detailed in the Industry Pioneers section of this publication.

In the 1950s, while working at Mobil Oil, American chemical engineers Charles Plank and Edward Rosinski were researching various catalysts. During their research, they decided to test zeolite as a catalyst for catalytic cracking. Plank and Rosinki's research on zeolite catalysts showed superior activity and selectivity, which led to dramatically higher gasoline yields during the cracking process. According to literature, the increased gasoil conversions could also be obtained without increasing gas or coke yields—two unwanted byproducts of cracking.[110,111]

The two chemists submitted their patent—*Catalytic cracking of hydrocarbons with a crystalline zeolite catalyst composite*—to the U.S. Patent Office in July 1960.[111] The patent submission and subsequent literature written by Plank described the catalyst as consisting of a finely divided crystalline aluminosilicate, having uniform pore openings between 6 ångströms (Å) and 15 Å, dispersed in an inorganic oxide matrix with a low sodium content.[111,112]

The technology patent was approved on July 7, 1964. Plank and Rosinski's patent laid the foundation for modern catalytic cracking (**FIG. 3**). Due to its molecular structure, zeolite catalysts are extremely effective in the reaction process—they have higher performance at lower pressures.

Five years after Plank and Rosinski's patent was approved, Robert Argauer and George Landolt—the two also worked at Mobil Oil—were the first to synthesize high-silica zeolite, which was commercially named Zeolite Socony Mobil-5 (ZSM-5). The two submitted the technology for a U.S. patent in 1969. The patent submission *Crystalline zeolite ZSM-5 and method of preparing the same* provided a detailed analysis of the novel crystalline aluminosilicate zeolite and its usefulness in cracking and hydrocracking processes, as well as within other refining processes (e.g., alkylation, isomerization) and petrochemical products production.[113] ZSM-5 catalysts are still used in refining and petrochemical plants around the world.

New petrochemical products/processes enhance everyday life.

Several new petrochemical products were discovered in the 1960s. These included Kevlar, linear low-density polyethylene (LLDPE) resins, a more cost-effective process to produce acrylonitrile and stretched polytetrafluorethylene (PTFE), which came to be known as Gore-Tex. With the significant expansion in the global petrochemical industry, *Petroleum Refiner* retitled the technical publication to *Hydrocarbon Processing and Petroleum Refiner* in 1961, then adopted the name *Hydrocarbon Processing* in June 1966. The publication's title—*Hydrocarbon Processing*—represented the integration of the global refining and petrochemical industries and the technical processes and operational know-how that are synonymous with refinery and petrochemicals production.

Acrylonitrile. The origins of acrylonitrile trace back to 1893 when French organic chemist and pharmacist Charles Moureu was the first to synthesize acrylonitrile. However, acrylonitrile did not find a commercial use until the 1930s—industrial producers used the material in applications such as acrylic fibers for textiles and synthetic rubber.[114]

Although the use of acrylonitrile was extremely effective in several applications, production was expensive and included multistep processes. In the late 1950s, the Standard Oil Co. (Sohio, later bp) discovered a cheaper processing route through selective catalytic oxidation to produce acrylonitrile. This research effort was led by Franklin Veatch. Veatch proposed that converting light refinery gases (e.g., aliphatic hydrocarbon propane) to oxygenates could be profitable. In 1953, funding was approved, and Veatch and his team began research efforts. With only 6 wk left of funding, Veatch's research team made a vital discovery when conducting a test run on propylene over a modified vanadium pentoxide oxidant, resulting in the production of acrolein—an additional oxidation step would produce acrylic acid.[114]

In 1955, the Sohio research team began testing oxidants as direct oxidation catalysts, leading to the process of converting propylene to acrolein in a single catalytic reaction step—the process used a bismuth phosphomolybdate catalyst.[114] According to literature, acrylonitrile was produced by feeding propylene, ammonia and air over the bismuth phosphomolybdate catalyst. The process resulted in ammoxidation (i.e., the Sohio process), which produced a 50% yield of acrylonitrile, with acetonitrile and hydrogen cyanide as coproducts.[114,115]

Approximately 4 yr after the start of research, the Sohio process was commercialized and a new $10-MM, 47.5-MMlb/yr plant was constructed in Lima, Ohio

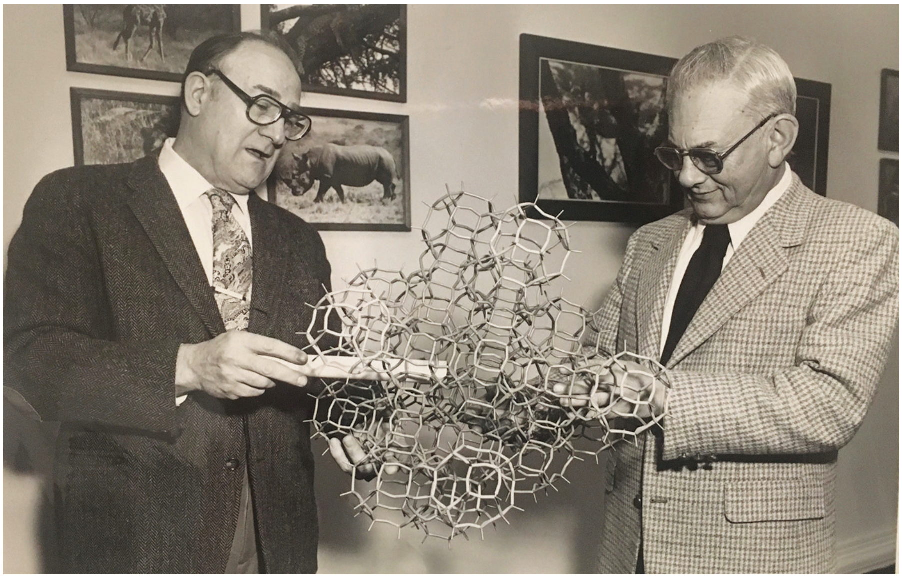

FIG. 3. Rosinski (left) and Plank (right) demonstrate their invention of zeolite catalyst prior to being inducted into the National Inventors Hall of Fame in 1979. Photo courtesy of the National Inventors Hall of Fame.

(U.S.). The plant was commissioned in early 1960. Upon the success of the Lima plant, Standard Oil Co. began licensing the Sohio process for the cost-effective production of acrylonitrile.

Acrylonitrile is used in numerous applications that touch the everyday lives of people around the world. It is a key ingredient in acrylic fibers (used in the production of clothing, carpeting, industrial yarns, blankets and drapes, among several other applications); in acrylonitrile-butadiene-styrene to produce appliances, automobile components, sports equipment, telephone and computer casings; specialty chemicals; polyols; nitrile rubber to produce fuel hoses, automotive belts and hoses; plastic resins; and adhesives and coatings.[114] The global acrylonitrile market reached approximately $12 B in 2020, with forecasts showing growth to more than $16 B by the late 2020s.[116,117]

FIG. 4. Stephanie Kwolek and others of the DuPont group that developed Kevlar. From left to right: Kwolek, Herbert Blades, Paul Morgan and Joseph Rivers. Photo courtesy of DuPont.

Kevlar. After graduating college in the mid-1940s, American chemist Stephanie Kwolek took a job with DuPont. During the 1950s/1960s, Kwolek's focus was on research and development of new synthetic fibers capable of performing in extreme conditions. Her initial researched focused on aromatic polyamides—a type of polymer that can be made into strong, stiff and flame-resistant fibers.[118] This work extended into the study of the polymers poly-p-phenylene terephthalate and polybenzamide. The focus of her team's research was to discover a new lightweight, strong fiber to use for light, strong tires (**FIG. 4**).[119]

During one experiment in 1965, Kwolek noticed the solution she was working on had a cloudy, thin and opalescent look when stirred, along with a low viscosity. According to literature, she also noticed that under certain conditions, many rodlike polyamides would line up in parallel (i.e., form a liquid crystalline solution), which could be spun into oriented fibers.[120] Upon testing the solution in a spinneret, Kwolek noticed that the fibers that were created were incredibly stiff and strong—these fibers had a high tensile strength-to-weight ratio (i.e., this new substance was five times stronger than steel on an equal weight basis).[119] Her discovery created a whole new field of polymer chemistry, which eventually led to the creation of modern Kevlar in 1971.

Kevlar's first commercial use was as a replacement for steel in racing tires in the 1970s. Since then, Kevlar has been used in more than 200 applications, including sporting and safety equipment, cables/ropes, boats, airplanes, motor vehicles, satellites, household items, and, most notably, in bullet-proof vests. In fact, on the day Kwolek passed away (June 18, 2014), DuPont announced that the one millionth Kevlar bullet-proof vest had been sold.[121] For her contribution to polymer research, Kwolek was the first woman to earn the Lavoisier Medal for Technical Achievement from DuPont.

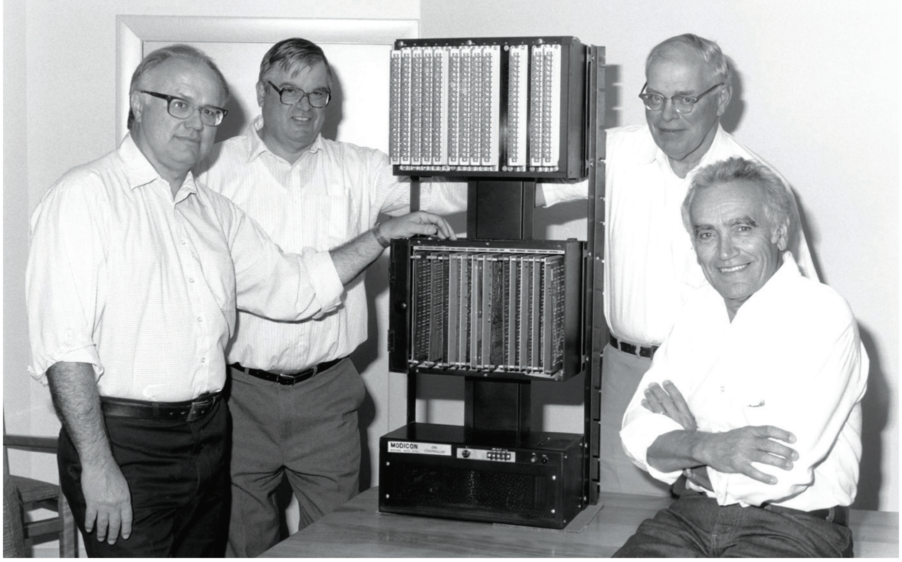

FIG. 5. The Bedford Associates group, who formed Modicon in 1968 after developing the world's first PLC, the Modicon 084. Left to right: Dick Morley, Tom Boissevain, George Schwenk and Jonas Landau. Photo courtesy of Schneider Electric.

LLDPE. In 1954, DuPont Canada was split off from its parent company Canadian Industries Ltd. The new company's first objective was to establish a research laboratory in Kingston, Ontario, Canada to identify new growth businesses, one of them being new applications for polyethylene (PE) production. The Kingston Research Center team focused on producing low-density resins by incorporating large amounts of alpha-olefin comonomers.[122] However, the product produced from pilot plant testing—which later became known as LLDPE—behaved differently than conventional low-density resin processes at the time, along with several other production challenges. Despite these setbacks, DuPont Canada greenlighted an investment in a new PE production plant.

Due to the economic market conditions in the late 1950s, DuPont Canada could only invest capital in one PE production plant. This facility—located in Corunna, Ontario (outside Sarnia)—could produce both high- and low-density PE (HDPE/LDPE).[122] The 275-MMlb/yr St. Claire River (SCLAIR) site—commissioned in 1960—used the same process produced in pilot plant testing by the Kingston Research Center team; thus, establishing the first commercial plant to produce LLDPE. The resin—named SCLAIR after the production site's location—was found to be stiffer, more heat resistant and tougher than conventional LDPE.[123] Several modifications to optimize the process were completed over the next several years, providing resins that would fetch premiums beyond commodity market prices.[122] The plant was so successful that DuPont Canada added a second PE production line at the Corunna site in 1976,

followed by licensing the SCLAIRTECH process worldwide in 1980—the technology can produce a range of products from LLDPE to HDPE.[124] DuPont Canada's PE business, including the St. Claire PE plant, was eventually purchased by Nova Chemicals in 1994.

In the 1970s/1980s, several other companies began to produce their own LLDPE resins. These included Dow Chemical, Union Carbide and bp Chemicals, among others. Union Carbide's LLDPE technology's origins emerged from research and development on a low-pressure, gas-phase fluidized bed process to produce HDPE. This process—known as the UNIPOL PE process (now licensed by Univation Technologies)—came to fruition in 1968 with the startup of the G-1000 plant in Seadrift, Texas (U.S.). The UNIPOL process extended its reach into LLDPE production in 1977.[125] By the late 1980s, more than 70% of the world's LLDPE production was produced via gas-phase polymerization—the basis of the UNIPOL process.[123] Today, several additional companies license their own LLDPE process, including Borealis, Chevron Phillips Chemical, INEOS and LyondellBasell, among others. LLDPE is used in many consumer goods such as plastic grocery/trash bags, shrink wrap, toys/playground and plastic gardening equipment, tubing, flooring and many other applications. Over the past 60 yr, the LLDPE market has significantly expanded, with forecasts showing the global LLDPE market will exceed $65 B by the mid-2020s and increase to more than $85 B by 2030.[126,127]

Gore-Tex. In the late 1950s, Bill Gore left his job at DuPont to pursue detailed research and analysis on the untapped potentials of PTFE.[128] The polymer PTFE was discovered by accident in the late 1930s by Roy Plunkett who was working at DuPont at the time. This discovery eventually led to the development of Teflon—the discovery of PTFE and the subsequent creation of Teflon was detailed in the 1930s history segment.

In 1969, Bill's son Robert (Bob) conducted experiments by heating rods of PTFE and stretching the material. However, on one such occasion, primarily out of frustration, he yanked the heated PTFE rod, causing it to stretch about 800%. After analysis, he noticed that the resultant material was incredibly strong, microporous (the structure was approximately 70% air), and contained several key benefits, such as low water adsorption and good weathering properties.[128,129] The expanded PTFE (ePTFE) was given the name Gore-Tex and sold commercially in the 1970s as a breathable, waterproof and windproof fabric for clothing (e.g., jackets).[129] Gore-Tex (ePTFE) found use in many applications over the ensuing decades, including in insulation, medical implants, high-performance fabrics, gloves, footwear and even on astronauts' spacesuits.

The PLC revolutionizes industrial automation. The invention of the PLC originated within the automotive industry. In the late 1960s, Bedford Associates—from Bedford, Massachusetts (U.S.)—was awarded a contract from GM Hydramatic [the automatic transmission division of General Motors (GM)]. GM wanted to replace its hardwired relay systems with a better electronic device.[130] Hardwired relay systems had several disadvantages: several relays were needed to control a single device, improper wiring of only one relay could cause the machine or entire system to shut down, systems were hard to troubleshoot and fix, and needed changes to the system often required reconfiguring the entire system.[131]

In 1968, the founder of Bedford Associates, Richard (Dick) Morley (known as the father of the PLC), unveiled the world's first PLC, the Modicon 084 (FIG. 5)—the technology was named Modicon (MOdular DIgital CONtroller) 084 since it was the company's 84th project.[132] The creation of the PLC meant that large banks of relays could be replaced by a single device. It also contained enough memory to retain loaded programs in the event of a power outage and worked well in harsh conditions.[131]

Bedford Associates soon adopted the company name Modicon and began to market PLCs. The company was also responsible for the invention of the Modbus in the late 1970s—Modus is a data communications protocol that enables electronic devices to communicate with each other.[133]

Modicon was acquired by Gould Electronics in 1977 and then by AEG in 1989. The company eventually became part of Schneider Electric in 1994 with the merger of AEG and Groupe Schneider—the merger took the name Schneider Electric in 1999.[134]

The invention of the PLC created a new era in automation technology. Today, PLCs are incorporated into refining and petrochemical plant operations to help monitor plant equipment, among other production actions. HP

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LEE NICHOLS, VP, Content/Editor-in-Chief

Excerpts from the 1960s: Petrochemicals rise in prominence and new know-how in refining processes

Old units do explode!

O. A. Pipkin, January 1960

This is the full story of the explosion that rocked the refinery of Cities Service in January 1959—the result of a series of human errors. Who would have thought that such a potential hazard existed in a coking process operating for more than 30 yr?

How well do you supervise?

J. E. Bigham, February 1960

Good supervisors should know the limits of their authority and responsibility. However, more important than the amount of their responsibility is how well they perform it—more important than their authority is their ability to apply it.

How much can you save with the isocracking process?

J. W. Scott, J. A. Robbers, N. J. Paterson and H. M. Lavender, April 1960

This article provides material balances for typical refineries converting middle distillate to gasoline. These cases demonstrate the advantages of the isocracking process for control of product distribution and quality.

When metals poison cracking catalyst

E. C. Gossett, June 1960

This article is an investigation of the effect of poisons on fluid catalytic cracking yields. It details how the hydrogen producing factor can be used as a criterion for operating a commercial unit and provide a measure for selecting feedstocks and determining catalyst replacement rates.

Mechanical specification of trays

H. C. Glitsch, August 1960

Mechanical aspects of tray specification are as important as the process itself. After chemical process and metallurgical specifications have been drawn, the tray must be mechanically designed to meet these specifications. This article provides an analysis of the items to cover when specifying fractionation trays.

Which to use—Relief valve or rupture disc?

P. A. Puleo, October 1960

The main difference between a relief valve and rupture disc is obvious—one will reseat and the other will not. The questions are: Where to use one or the other and when to use both? What system factors affecting disc and valve performance should be considered? What problems inherent in the services themselves should be considered (i.e., leakage, pressure limitations and settings, capacity, among others)?

Which acetylene feed is best?

D. C. Lockwood, November 1960

This article compares the effect of methane, ethane and propane on overall manufacturing costs. The effect of fuel, oxygen and investment costs for various paraffin feeds are thoroughly discussed.

To engineering contractors: A checklist for project engineers

February 1961

Checklists can resolve many questions about a project in the shortest time. One of the most important lists in Phase 1 (the pre-contract stage) is the construction questionnaire. This article provides questions that should be answered about the construction site.

New uses spark propylene growth

T. C. Ponder, March 1961

Propylene, one of the first petroleum raw materials used in chemical manufacturing, is being studied by petrochemical manufacturers as though it were a new discovery. This exciting new look at propylene is due to the development of several new processes into commercial production. This trend can mean increasing demand for high-purity propylene.

Design tips for refinery tank farms

A. H. Younger, July 1961

Three variables control the design of refinery storage tanks, pumps and miscellaneous items: crude yields, sales estimates and refinery production forecasts.

This article shows how these variables are predicted, along with detailed examples on the design of storage tanks and accessories.

Don't be confused by rotary pump curves

A. A. Zalis, September 1961

Some engineers throw up their hands in despair when a screw or gear pump operates at viscosities other than those shown on pump curves. This article provides a simple way to extrapolate rotary pump curves and find operating characteristics at other viscosities.

For ethylene oxide, it is uphill for the second billion

J. Gordon, October 1961

Process improvements and aggressive development of new markets point to steady growth for ethylene oxide on its way to 2 Blb/yr.

Is epoxidation in your future?

J. Gordon, April 1962

Epoxidation is in your future if you are interested in plastics and plasticizers made from abundant and low-cost materials. Major growth in epoxidation may be attributed to improved processing techniques, greater variety and quality of products.

Comparing cooling towers: European vs. U.S.

J. W. Hubenthal, June 1962

Industrial expansion globally has been witnessed within the cooling tower sector. This article provides a comparison of fundamental differences in cooling tower design between the U.S. and Western Europe.

Now—Make jet fuel from coal

M. Letort, July 1962

Jet fuel can now be made from coal using established catalysts and hydrogenation techniques. Ample supplies of coal tar fractions offer an additional source for high-energy jet fuels.

Management's role in the creative 'climate'

A. Wintringham, October 1962

This work details what management can do to set up a good corporate climate for encouraging and using the creative potential of engineers and how to develop young engineers along creative lines.

Polymethylbenzenes go commercial

L. T. Eby and P. E. Neman, March 1963

Five C_9–C_{10} aromatics have reached the commercial market. Following cumene, pseudocumene, naphthalene, mesitylene and durene are more alkyl-substituted benzenes reaching for commercial status.

Make resins from styrene-butadiene

I. A. Eldib, June 1963

Now resins from styrene-butadiene can be made using sodium catalyst or emulsion copolymerization. This article provides data on costs, raw materials and process variables, together with uses and applications.

Which steel for refinery service?

C. H. Samans, November 1963

This articles describes selection and evaluation of carbon steel, ferritic stainless steel and austenitic stainless steel for refinery service above 650°F.

How to evaluate contract maintenance bids

H. D. Dobe, January 1964

In this article, the author suggests two checklists: One to evaluate eligible contractors and the other on precontract information to the bidders. Some of the items discussed include:

- Whom do you invite to bid?
- How do you select the contractor?
- Conference vs. solitary briefings to bidders
- Annual vs. as-needed contracts
- Types of contracts.

Better lab practices in chromatography

J. Q. Walker, April 1964

These hints will help you make your chromatographic equipment safer, faster and more productive. They include tips on filament and fire protection, carrier gas purification, optimum column and temperature control, better pressure control and reorder operation.

What's optimum exchanger pressure drop?

F. W. Lohrisch, June 1964

There is an optimum pressure drop in every heat exchanger at which the purchase price plus the operating costs are reduced to a minimum. Increasing fluid velocities increase heat transfer and pressure drop and lower the purchase price but increase pumping power requirements. What is optimum? This article provides equations and nomographs that consider physical properties of the fluid, purchase price of the exchanger, working hours, power costs, etc., to find the optimum pressure drop for a particular exchanger.

Practical design of flare stacks

G. R. Kent, August 1964

A key factor in flare stack design is in the escape time for personnel assumed to be at the stack base at the time of ignition. In this article, a basis is provided to limit the maximum heat radiation at the stack base. The effect of flame characteristics, gas flow, escape time, heat radiation and wind on stack diameter and height are covered in this design method.

Cut heat costs with chemical cleaning

J. H. VanSandt, December 1964

This case history shows that a refinery can cut fuel costs by $250,000/yr by picking up an additional degree of temperature in all its heat exchangers. Types of exchanger deposits are described together with techniques for removing them chemically, along with steps in chemical cleaning.

Petrochemicals: Big drive in '65

F. G. Sawyer, January 1965

With the usual ups and downs, and certain petrochemicals dragging, overall production, sales and capacity utilization look for the best year yet in 1965.

How to reduce hydrogen plant corrosion

K. L. Moore and D. B. Bird, May 1965

High temperature and wet carbon dioxide (CO_2) were the major causes of corrosion in a U.S. hydrogen plant. Here are the details of how the problems were solved. Subjects discussed include Incoloy furnace tube corrosion from residual welding slag, high-temperature overstress and thermal fatigue, wet CO_2 corrosion, chloride stress corrosion cracking of stainless steel in MEA service, hydrogen attack and denickelification of monel condenser tubes.

Camel LNG plant: World's largest

C. G. Filstead, July 1965

The third liquefaction line is now in operation at Arzew, Algeria. It is the world's first commercial scheme to liquefy natural gas for export. Here is how it is operating.

Design criteria for large urea plants

L. H. Cook, February 1966

A 1,500-metric tpd, single-train urea plant is now economically feasible. This article provides criteria for optimum design.

New catalyst for Sohio process

What's HapPenIng, June 1966

The Standard Oil Co. (Ohio) will begin construction in the spring of 1966 on a plant in Lima, Ohio, to produce a new, alternative catalyst to be used in Sohio's acrylonitrile process. Commissioning is scheduled for early 1967.

What's the future for PVC?

G. Olivier, September 1966

Because it is so well established in the thermoplastic field, polyvinyl chloride should have an annual growth rate during the next 10 yr more than 12%.

Essential information for piping design

R. W. Judson, October 1966

Three major source documents are essential for good piping design: engineering flow diagrams, nomenclature and equipment elevations. This article explains each in detail, providing content and source of these essential documents.

"Clipping Method" for turnaround scheduling

C. K. Gimlin, January 1967

Job sequences are compiled on a written work order. Then, jobs for each craft are "clipped" from the work order and placed in job folders. These are transferred to a daily work schedule for each craft. As the turnaround progresses, changes in work requirements can be quickly rescheduled using the system.

How to handle a safety inspection

V. J. Whitehorn and H. W. Brown, April 1967

Periodic inspections are a key part of a good safety and fire protection program. This article provides a checklist to help personnel ensure their plant is getting the attention it needs.

Less sulfur in the air from fuels?

R. C. Mallatt, December 1967

Although the use of petroleum and natural gas fuels is growing, there is less air pollution from the sulfur in these fuels. In the U.S., investments in processes which desulfurize have reached approximately $700 MM, according to a recent industry survey.

Learn about analog computers

T. W. Cadman and T. G. Smith, February 1968

This series describes the basic concepts of analog computers. It will detail how analog computers can be used to simulate processes and to solve problems peculiar to the HPI. Among the items to be covered include amplitude scaling, time scaling, process simulation, circuit design, diode switching, function generation, memory and logic, and future roles.

Noise pollution: A new problem

J. M. Hopkins and R. H. Congelliere, May 1968

Air and water pollution have stirred a new interest—noise pollution. This article discusses the effect of excess noise on employees, existing legislation designed to control industrial noise and an effective noise-control program.

Compare DGA and MEA sweetening methods

J. C. Dingman and T. F. Moore, July 1968

Among the processes for sweetening natural gas, monoethanolamine (MEA) ranks at or near the top in number of commercial installations. Now, a very similar process, using a chemical called diglycolamine (DGA), presents credentials which appear to make it extremely competitive with the long established MEA process.

Petrochemicals: Still fine in '69

F. G. Sawyer, January 1969

Petrochemicals remain the pacesetters of the HPI. Last year proved better than expected, but the same problems of price fatigue and overcapacity plagued certain areas. Discounting short-term variations, the long-term outlook is excellent.

Optimum: Hydrocrack + reform

J. R. Kittrell, G. E. Langlois and J. W. Scott, May 1969

For best refining operations, it is important to consider the yield-octane relationship between hydrocracking and modern catalytic reforming. This article provides some generalized correlations.

Olefins by dehydrogenation-extraction

D. B. Broughton and R. C. Berg, June 1969

By combining catalytic dehydrogenation of linear paraffins with molecular sieve extraction, high-purity linear internal mono-olefins are produced in good yield at a cost of approximately $0.02/lb.

Furnace tubes: How hot?

J. M. Lenoir, October 1969

The measurement of surface temperatures for furnace tubes is important to achieve optimum operation. Not hot enough: Uneconomical processing; too hot: Quicker tube failures.

Ideas for gas plant automation

B. A. Eckerson, December 1969

This article provides a look beyond the control of simple operating variables. It provides practical ideas—many already tested—for the control of air coolers, sulfur plants, plant emergencies, truck loading and the operation of absorption oil units. HP

LEE NICHOLS, VP, Content/Editor-in-Chief

The 1970s: Crises, clean air, plastic bottles and the DCS

The 1970s were marked by several historical events that affected not only the hydrocarbon processing industry (HPI) but nations around the world. The decade witnessed two oil crises that would disrupt the global supply of oil and increase prices substantially. New regulations by the U.S. and Europe ushered in an era of clean fuels standards that are still in transition today. Novel technologies introduced in the 1970s revolutionized emissions reduction from vehicles' tailpipes, advanced process controls and automation, and changed the way society drinks carbonated beverages.

The decade also witnessed advances in catalytic processing technologies, such as the commercialization of catalytic dewaxing, wax hydroisomerization and continuous catalytic reforming (CCR).[135] For example, Mobil developed the first catalytic dewaxing process in the mid-1970s. The technology—referred to as the MDDW process—utilized the company's Zeolite Socony Mobil-5 (ZSM-5) catalyst to increase the cold flow properties of diesel (the invention of the ZSM-5 catalyst was detailed in the 1960s history section).[136] In 1971, UOP began operations on the first CCR Platforming unit at the Coastal States refinery in Corpus Christi, Texas (U.S.). According to literature, the CCR section enabled refiners to continuously remove coke accumulating on the catalyst. This allowed lower reforming reaction pressures to increase reformate and hydrogen yields, higher reaction temperatures to achieve higher octane levels for gasoline blending—thus enabling lead-free gasoline—and increased production of aromatics for use as petrochemical feedstocks.[137]

Two crises stress the importance for energy security. The 1970s were rocked by two global crises: The oil embargo of 1973 and the oil crisis of 1979. These two events had detrimental effects on oil importing nations around the world, as well as stressed the importance of energy security.

Oil embargo of 1973. The first oil crisis to affect the global economy in the 1970s was the Organization of Petroleum Exporting Countries' (OPEC's) oil embargo in 1973–1974. The embargo was a retaliation against countries that supported Israel during the Yom Kippur War with Syria (i.e., the U.S., Canada, Japan, and a few African and Western European nations).[138] It banned petroleum exports to targeted countries and incorporated crude oil production cuts, leading to a quadrupling of oil prices—oil prices increased from \$3/bbl to nearly \$12/bbl by early 1974, an increase of 300%.[139]

The embargo had detrimental effects on nations that were dependent on foreign oil to satisfy domestic demand. Many nations enacted oil rationing programs, as well as banning fuels usage (e.g., driving, flying) on various days. The high price of oil even led several countries to the brink of recession and proved that oil could be used as an economic weapon.[139]

In March 1974, peace talks between Israel and Syria led to the eventual lifting of the oil embargo. However, this would not be the last time within this decade that the world would be caught in a global oil price crisis.

Oil crisis of 1979. The second crisis that significantly affected global oil prices in the 1970s was due to the Iranian Revolution. The revolution, which began in early 1978 and ended a year later, led to the toppling of the country's leader, Shah Mohammed Reza Pahlavi, and installed Sheikh Khomeini as grand ayatollah. The year-long revolution was responsible for knocking approximately 4.8 MMbpd of oil production offline. Although this represented only 7% of the world's oil production at the time, it led to global oil prices nearly doubling to \$39/bbl.[140]

In a little more than 6 yr removed from the oil embargo crisis, history began to repeat itself. Several countries rationed supplies, governments invested billions of dollars in research to find an alternative to oil, and many countries either switched or began to explore switching domestic power generation from oil to other feedstocks, such as coal, natural gas or nuclear.[140]

Both the 1973 oil embargo and 1979 oil crisis had dramatic effects on the global marketplace. However, the underlying theme of these global events brought to light the necessity for energy security, a concept that continues today.

The Clean Air Act of 1970 ushers in a new era of environmental awareness/action. As countries modernized and produced fuels and products for domestic and international markets, a lingering challenge could be felt by local populations: air pollution. Not only did manufacturing plants, refineries, chemical and petrochemicals facilities, factories and other industrial operations produce air pollutants, gasoline burned in internal combustion engines (i.e., automobiles) filled the skies with pollutants such as hydrocarbons, carbon monoxide and nitrogen oxides.

In efforts to reduce air pollution, the U.S. Environmental Protection Agency (EPA) initiated a series of laws and amendments to various industries. The first federal legislation passed to address air pollution in the U.S. was the Air Pollution Control Act of 1955. Although the law did not tackle air pollution directly, it provided funding for research relating to air pollution control.[141] Eight years later,

the U.S. EPA passed the Clean Air Act of 1963, which enabled the U.S. government to take direct action to control air pollution.[141] In 1965, an amendment to the Clean Air Act of 1963—the Motor Vehicle Air Pollution Control Act—created the first federal set of standards for vehicle emissions.[142]

The Clean Air Amendments of 1970 significantly strengthened federal authority to regulate emissions from both industrial and mobile sources (**FIG. 1**). This amendment included the following major components[141]:

- It established the National Ambient Air Quality Standards (NAAQS) for pollutants in outdoor air that can be harmful to the public or the environment—i.e., carbon monoxide, lead, particulate matter, ozone, nitrogen dioxide and sulfur dioxide.[143]
- It established New Source Performance Standards to determine how much air pollution should be allowed by different industries.
- It established the National Emission Standards for Hazardous Air Pollutants to cover all air pollutants not covered by the NAAQS.
- It called for aggressive air pollution reduction goals—some as high as 90%—for the mobility sector.

The significance of the Clean Air Act of 1970 was that it gave the U.S. EPA enforcement authority over domestic emissions levels, as well as required U.S. states to issue plans (State Implementation Plans) on adhering to national air pollution standards. This model is still in use today. The Clean Air Act had several additional amendments added to it over the next 30 yr, including major additions during the 1990s to address acid rain, ozone depletion and toxic air pollution, as well as establishing Reid vapor pressure standards and new regulations on fuels sold during the months of May–September (i.e., summer-grade fuel).[141]

Although the Clean Air Act was intended to reduce air pollution, especially from the automobile industry, challenges existed on how to mitigate pollutants from an automobile's tailpipe. A solution was put forth in the mid-1950s but did not fully materialize for the auto industry until the mid-1970s. This technology can still be found on nearly every vehicle in use today: the catalytic converter.

The catalytic converter. Although prototypes of catalytic converters were introduced in France in the late 1800s, the modern catalytic converter was first patented in the mid-1950s by a well-known pioneer in the refining industry, Eugene Houdry. Houdry's pioneering work in the creation of catalytic cracking was detailed in the 1930s history section.

Houdry began research and development on this technology after studies were released that showed alarming increases in smog in the Los Angeles, California (U.S.) area. These Los Angeles area smog studies in the early 1950s also played a part in similar studies in Western Europe. Around 1956, both French and German scientists were engaged in research to mitigate smog in several major cities in France and Germany.[144] These scientists noticed that several of their respective urban areas suffered from dense air pollution similar to that referenced in the Los Angeles smog reports. Both teams' research into mitigating vehicle emissions eventually led to the implementation of Directive 70/220/EEC in 1970.[145] This ground-breaking piece of legislation was the impetus to setting emissions standards for light- and heavy-duty vehicles in Europe. The directive eventually led to the introduction of the Euro 1 standard in 1992 (implemented for passenger cars in 1993), the removal of leaded petrol from filling stations in Europe and the adoption of three-way catalytic converters.[144,146,147] European emissions standards (i.e., Euro 1–6 and Euro I–IV; Euro 7/VII are expected to be implemented in the mid-2020s)[145,148] would become a global standard for many countries around the world over the next few decades in efforts to adhere to clean fuels regulations.

In the U.S., Houdry was concerned that emissions from smokestacks and automobile exhaust were leading to significant air pollution.[149] To reduce emissions from these sources, Houdry created the company Oxy-Catalyst to develop catalytic converters. His first designs were aimed at mitigating emissions from smokestacks. This effort was followed by the development of catalytic converters for low-grade gasoline-powered forklifts used in warehouses.[150] In the mid-1950s, Houdry fixed his sights on developing catalytic converters for automobile engines. His technology was patented under the title Catalytic Apparatus to Render Non-Poisonous Exhaust Gases from Internal Combustion Engines on April 17, 1956 (**FIG. 2**).[151]

However, the widespread adoption of catalytic converters by the automobile industry did not take effect until the passing of the U.S. Clean Air Act and subsequent amendments. These laws dictated strict regulations on vehicle emissions, as well as the continued removal of lead from gasoline—incorporating tetraethyllead (TEL) into gasoline was first used in the 1920s to prevent knocking in internal combus-

FIG. 1. U.S. President Richard Nixon signs the Clean Air Act of 1970, which called for a significant reduction in air pollutants from industrial and mobility sectors. Photo courtesy of the U.S. National Archives.

tion engines. The first TEL reduction standards—part of the U.S. NAAQS standards—were passed into law in the early 1970s. The recognized adverse impacts of emissions from leaded gasoline on human health would lead to the eventual removal of lead from gasoline over the next few decades—the U.S. banned leaded gasoline in on-road vehicles in 1996.[152] Lead was also detrimental to the operation of catalytic converters. Lead acts as a catalyst poison by forming a coating on the catalysts inside the converter, leading to inactivity and increased emissions.[149] Numerous countries in Asia, Africa, Europe and South America followed suit, and, in July 2021, the last batch of leaded gasoline was sold in Algeria. This occasion marked the end of the use of leaded gasoline globally.[153]

After the adoption of the Clean Air Act, automobile manufacturers began producing new lines of vehicles that included catalytic converters. However, the Clean Air Act amendments of the 1970s put stringent restrictions on the removal of carbon monoxide, hydrocarbon and nitrogen oxide emissions. Catalytic converters available at the time were able to reduce carbon monoxide and hydrocarbon emissions but not nitrogen oxide. This challenge was solved by a group of engineers working at Engelhard Corp. (now part of BASF) in Iselin, New Jersey (U.S.). This group was led by chemists Carl Keith and John Mooney. Their revolutionary three-way catalytic converter—introduced in 1973—was able to reduce all three pollutants from a vehicle's tailpipe. According to literature, the technology used rare-earth and base metal oxide components in the catalyst together with platinum and rhodium in a ceramic honeycomb, with tiny passages coated with the catalytic material.[154] This enabled their design to remove carbon monoxide, hydrocarbon and nitrogen oxide in a single catalytic component.[154] The three-way catalytic converter was installed in most vehicles in 1976 and is still in use today.

The evolution of the distributed control system. In 1959, Texaco started operations on the first digital control computer at a refinery. This system—a Thompsom Ramo Wooldridge RW-300 computer—became the first fully automatic, computer-controlled industrial process and ushered in the computer-integrated manufacturing era in the HPI. A detailed account of this technology can be found in the 1950s history section of this publication.

Additional technologies, such as programmable logic controllers (PLCs), were incorporated into plant operations in the late 1960s/early 1970s. These devices were pioneered by Richard (Dick) Morley of Bedford Associates (now part of Schneider Electric) and Odo Josef Struger of Allen-Bradley (now part of Rockwell Automation). Both inventors are known as the fathers of PLCs—Struger even coined the acronym PLC.[155] A history of the PLC is detailed in the 1960s history section. Allen-Bradley also introduced Data Highway in 1979, which was the first plant-floor network designed to support remote programming and messaging between computers and controllers, replacing miles of wiring in plant operations.[156]

In 1975, another revolutionary technology was unveiled to optimize refining and petrochemical plant operations, the distributed control system (DCS). The first DCSs were introduced by Honeywell and Yokogawa. Bristol (now part of Emerson Process Management) also introduced the UCS3000 in 1975, which was the first microprocessor-based universal controller.[157] Prior to the DCS, plant operations were controlled via board operation (i.e., controllers were mounted on large instrument panels). However, through the evolution and wide-scale availability of microcomputers and microprocessors, the DCS was created to control manufacturing processes in several industries, including oil refining and petrochemicals production.[157]

Honeywell and Yokogawa both introduced their own DCSs around the same time—Yokogawa created CENTUM (FIG. 3), while Honeywell introduced the TDC2000 platform. According to literature, Yokogawa's journey to the DCS included applying microprocessors to control systems. These control systems were divided into three basic components: human-machine interface, controllers and control bus. The system was named DCS and was instrumental in controlling various functions of plant operations (e.g., flow).[158]

In the early- to mid-1970s, Honeywell worked extensively at optimizing automation technologies, as well as focusing on advancing process controls. The company introduced the TDC2000 (TDC stood for total distributed control) system in 1975. This system provided a centralized view of processes within the plant and utilized a data highway that could link various sensor data to a central location.[159] Plant personnel could monitor and modify several control loops in a single system. TDC2000 was used globally for a decade until being replaced by TDC3000 in 1985, followed by Experion in the 2000s.

In 1978, Valmet introduced the Damatic Classic automation system, which was installed at Pankaboard's board mill in Lieksa, Finland. The DCS operated for nearly 40 yr at that location before being replaced by the latest iteration (Valmet DNA) in 1998.[160]

Other digital companies introduced new technologies during the 1970s and 1980s to optimize process controls and automation for the HPI. In the late 1970s, the Massachusetts Institute of Technol-

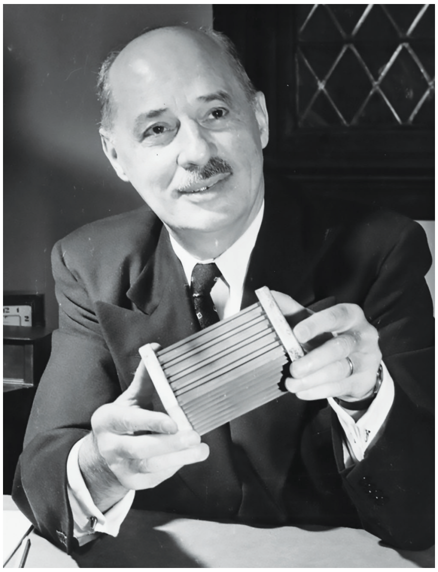

FIG. 2. Eugene Houdry holding a small catalytic converter. Photo courtesy of Sunoco and the Science History Institute.

FIG. 3. Yokogawa introduced the CENTUM DCS in 1975. Photo courtesy of Yokogawa.

ogy (MIT) created an Energy Laboratory to facilitate collaboration between university and industry.[161] This effort materialized out of the energy crisis of the 1970s. Led by MIT Professor of Chemical Engineering Larry Evans and funded by the U.S. Department of Energy, the Advanced System for Process Engineering (ASPEN) project began in 1977.

According to literature, the ASPEN project set about to develop a general-purpose simulation system that could be used by chemical engineers across the entire process industries. The result of the project was the next-generation process simulator named ASPEN. This technology could simulate large, complex processes involving highly non-ideal chemical components, coals and synthetic fuels, as well as electrolyte and multiphase systems.[161]

In 1981, the software was commercialized by the new company, AspenTech, which released its first product, Aspen Plus, in 1982.

Several direct digital control technologies were released in the 1970s, which included Foxboro's (now part of Schneider Electric) FOX 1 system for plant monitoring and process control, Fisher Controls' (now part of Emerson) DC² system and PROVOX DCS, Taylor Instrument Co.'s and Baily Controls' (both companies are now part of ABB) 1010 system and 1055 system, respectively.[162,163]

Process automation continued to evolve over the next several decades, including the move to ethernet-based networks, fieldbus installations, wireless systems and protocols, increased cyber defenses, remote transmission, and many other advances to optimize plant operations.

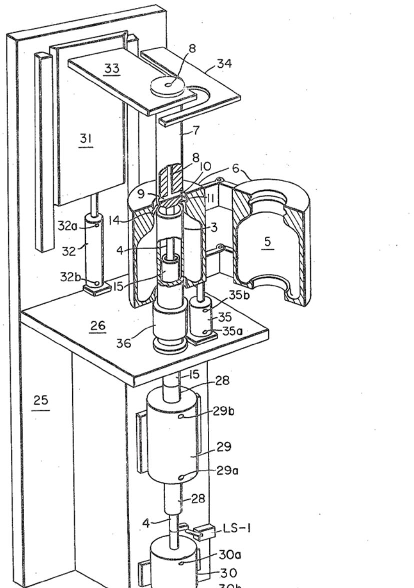

FIG. 4. A perspective view of Wyeth's invention as submitted in his patent. Photo courtesy of the U.S. Patent Office.[170]

Polyethylene terephthalate: Solving the carbonated liquids container challenge. In 1941, DuPont scientists John Whinfield and James Dickson expanded on Wallace Carothers'—a fellow DuPont colleague—work on synthetic fibers. Carothers' research was instrumental in the discovery of neoprene, nylon and other synthetic fibers. These discoveries were detailed in the 1930s history section.

Through their research, they discovered how to condense terephthalic acid and ethylene glycol into a new polymer that could be drawn into a fiber.[164] Their work eventually led to the development of polyethylene terephthalate (PET). Whinfield and Dickson patented their discovery in Great Britain in mid-1941 (and later in the U.S. in 1945);[165] however, due to wartime secrecy, the invention was not made public until several years later.[166] PET would become the basis for many products used in everyday life, and, today, PET is the fourth most produced polymer. One of the primary reasons for its popularity is its stretchability into long hard fibers, which makes it ideal to produce films and containers, among other items, that are lightweight, hard and durable. Using blow molding on PET created a product in the early 1970s that would revolutionize how societies enjoy different beverages: the plastic bottle.

The first plastic bottle was created in the late 1940s by cosmetic chemist Jules Montenier. At the time, Montenier was trying to find a suitable container for his liquid antiperspirant called Stopette—prior to his invention, antiperspirants were applied as a cream or in liquid form by dabbing it on using an applicator or pad.[167] He turned to a new chemical polymer discovered approximately a decade before called polyethylene (PE)—the discovery of PE was detailed in the 1930s history section of this publication. In 1947, Montenier partnered with the Plax Corp. of Hartford, Connecticut (U.S.)—the company used blow molding to manufacture plastic Christmas tree ornaments.[167] Their partnership produced the Stopette spray bottle, which was first commercially sold in July 1947.[167] This event marked the beginning of plastic containers competing against glass.

However, plastic containers remained expensive until the invention of high-density PE (HDPE)[168] in the 1950s by J. Paul Hogan and Robert L. Banks while working at Phillips Petroleum Co. in Bartlesville, Oklahoma (U.S.)—the discovery of HDPE is detailed in the 1950s history section. Several new uses of plastic bottles were commercialized over the next two decades, including the plastic milk bottle (patented by Roy Josephsen, Joseph Tino and Charles Fulcher of W. R. Grace & Co.) in 1965.

Like Whinfield and Dickson, Nathanial Wyeth also worked at DuPont. Prior to the late 1960s, he invented several products for the company, including a machine that built dynamite cartridges automatically, which kept workers from inhaling poisonous nitroglycerin powder; and a machine to manufacture Typar, a polypropylene (PP) fabric used in industrial sectors such as construction.[169]

In 1967, Wyeth began experimenting with the possibility of using plastic bottles to store carbonated beverages. Conventional wisdom at the time was that plastic bottles could not hold the pressure of carbonated beverages and would explode. To test this theory, Wyeth filled a plastic detergent bottle with ginger ale, sealed it and placed it in his refrigerator. According to literature, the next morning, the bottle had swelled so much that it was lodged between the refrigerator shelves.[169] This experiment proved to Wyeth that a stronger plastic was needed to withstand the pressure of carbonated liquids.

His initial work was with PP; however, he switched to PET due to its superior elastic properties.[169] After several experiments, Wyeth invented a machine that produced a "hollow, biaxially-oriented, thermoplastic."[170] This machine would strengthen the plastic by creating a mold that had nylon thread running in a diamond crisscross pattern. When the mold was pressed, the molecules aligned in a biaxial fashion.[169] This created a light, clear and resilient product that could

withstand the pressure of carbonated liquids. On May 15, 1973, Wyeth received a U.S. patent for his biaxially-oriented PET bottle machine (**FIG. 4**).

Although PET plastic bottles were more expensive than glass when first introduced into the market, they had many more benefits, such as they were lighter, they were not easily breakable and they could be resealed. Eventually, due to increased manufacturing, the cost for PET plastic bottles decreased significantly.[171] Companies like Coca-Cola and Pepsi brought PET plastic bottles to the global masses, and PET plastic bottle usage has soared globally over the past several decades. In 2021, more than 580 B PET plastic bottles were produced (an increase of nearly 100 B/yr since 2016), reaching a total market value of nearly $40 B—industry reports forecast the PET plastic bottle market reaching more than $50 B by 2027.[172,173]

Infrastructure rises from the Saudi desert: Jubail, Yanbu and the master gas system. In 1975, Saudi Arabia's government commissioned the construction of two new industrial cities, one on each of its coasts—Jubail in the east and Yanbu in the west. These cities were the results of the country's growing wealth from oil production and global trade and would serve as major industrial complexes to produce refined fuels and petrochemical products to satisfy domestic demand and for export.

Around the same timeframe, Aramco—the company would not adopt the name Saudi Aramco until the late 1980s—began work on the country's master gas system.[174] The system's goal was to gather and utilize associated natural gas that was being flared (wasted) from domestic production and use it as a low-cost fuel for industrialization.[175] This capital-intensive project included the construction and operation of gas gathering infrastructure, treating and processing facilities, and a transmitting system. By the mid-1980s, the master gas system was able to produce up to 2 Bft^{3}d of natural gas.[175] Over the next 40 yr, the company significantly expanded the system's total capacity, with the ability to produce approximately 12.5 Bft^{3}d of natural gas by the early 2020s.

Jubail Industrial City. Jubail's origins date back more than 7,000 yr and garnered fame in 1933 as the initial landing spot for Standard Oil of California (now Chevron) geologists in their search for oil in the country.[176]

In the mid-1970s, Jubail was little more than a fishing village; however, it had several benefits for the country. The city's location was ideal for shipping, it had ample water supplies to cool industrial plants and it was near crucial domestic oil production fields.[177]

The scope of the megaproject was to convert Jubail into a large-scale industrial city. The Saudi government selected two agencies to oversee the city's construction: The General Petroleum and Mineral Organization (PETROMIN) and the Saudi Basic Industries Corp. (SABIC). The project developers selected American-based engineering, construction and project management firm Bechtel to design and build the industrial city. Jubail Industrial City was an effort by the Saudi government to reach self-sufficiency in refined and petrochemical products.

The city, which covers more than 1,000 km^2, includes a multitude of industrial infrastructure, including the 440,000-bpd SATORP refinery (a JV between Saudi Aramco and TotalEnergies) and the SADARA petrochemical complex (a JV between Saudi Aramco and the Dow Chemical Co.).

Yanbu. On the country's west coast, the Saudi government decreed the construction of a second industrial city in Yanbu. The city's origins date back more than 2,500 yr when it was used as a staging point on the spice and incense route from Yemen to Egypt and various countries around the Mediterranean.[178] This sister industrial city to Jubail would be smaller, but due to its proximity on the Red Sea, would be crucial as an import/export port for the country. Over the next several decades, additional hydrocarbon processing facilities would be built, including refineries, petrochemical plants and other supporting infrastructure (e.g., pipelines, storage).

Today, Jubail and Yanbu are the first- and fourth-largest industrial cities, respectively, in the world.[179]

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Excerpts from the 1970s: Maintenance, optimization, safety and digital technologies

You can predict turbomachinery reliability
J. S. Sohre, January 1970

Reliability factor curves have been drawn as a guide to probable trouble in components or entire turbomachinery systems. Designers can use reliability factors to upgrade weak system components. Maintenance can use the factors to pinpoint probable trouble areas.

Low-sulfur fuels are different
C. W. Siegmund, February 1970

A change to low-sulfur fuel oils can change the requirements for storing and pumping these fuels. Fuels from low-sulfur crudes will have a higher viscosity, while desulfurization of high-sulfur stocks will produce lower viscosity but higher costs.

What's ahead for aromatics?
S. Field, May 1970

In this decade (1970s), chemicals will require 230,000 bpd and gasoline 1 MMbpd of aromatics. Refiners will face new problems in butene, xylene and toluene production, conversion, processing and extraction to meet this demand.

Refiners face challenges of 1970s
J. D. Wall, December 1970

Challenges facing the refining industry will cause shifts in locations of refining centers, product distributions and processing styles. Changes will take place to accommodate growing demand for more consumer products and chemical feeds. The needs are clear. The solutions are less clear.

A bigger role for cat reforming
H. L. Hoffman, February 1971

Catalytic reforming of naphthas to produce aromatics is growing at an accelerated pace. The HPI looks to this process for aromatics to improve antiknock ratings of motor fuels and to furnish feeds for petrochemicals.

Optimize olefin cracking coils
J. L. de Blieck and A. G. Goossens,
March 1971

Based on simple kinetics and extensive pilot and commercial plant operations, the radiant cracking coils can be optimized for product pattern and investment.

Natural gas grows in world use
J. Salkeld, April 1971

The U.S. and the USSR have long dominated the use of natural gas. Now, with better pipelines and LNG, gas is on the move. It is becoming a bigger factor in the energy picture of most world areas. The article examines what can be expected in the judgment of an authoritative market analyst.

Synthetic fiber feedstocks
P. Leprince, July 1971

Synthetic fibers—nylons, polyesters, acrylics and polyolefins—show growth rates above 10%/yr. With this fiber growth and its increasing demand on HPI feedstocks, present data indicates ample raw material supplies with minimum supply-demand dislocations.

How styrene grows in Europe
July 1971

From 500 MMlb of styrene converted into plastics in 1960, markets have grown to about 2.5 Blb today. A future annual growth rate for styrene monomer of 10%–12% is expected.

Flue gas desulfurization technology
A. B. Welty, Jr., October 1971

How do we keep sulfur out of the air? Flue gas desulfurization is one way that many are considering, and a few are trying. This article is an analysis of the possibilities for making this approach work. It is "must reading" if you have a flue gas problem.

Wastewater treatment
M. R. Beychok, December 1971

Stronger laws and tougher enforcement make design of the wastewater treatment system more important, but state-of-the-art processes can meet the challenge when properly used by the design engineer.

Better gasoline chromatography
H. Boer and P. van Arkel, February 1972

Multistage chromatography is used to determine the paraffin-naphthene-aromatic composition of products in the naphtha boiling range.

Optimize the ethylene complex
A. J. Gambro, K. Muenz and M. Abrahams, March 1972

This article details how planning, optimization and process selection can maximize profits for a 1 Blb/yr ethylene petrochemical refinery.

Can olefins meet '70s needs?

R. I. Silsby and N. E. Ockerbloom, March 1972

To fill a potential world demand of 60 MMlb/yr by 1980, olefins plants must meet these prerequisites and challenges: plant size, feedstocks, technology, engineering, inflation and finance.

Make SNG from coal?

G. E. Klingman and R. P. Schaaf, April 1972

Coal is a vast reservoir of energy that cannot be fully tapped until processes are developed for conversion to a useful form, such as substitute natural gas (SNG). The race is on to get the best process first. This article examines the frontrunners.

Regenerate reformers continuously

B. J. Cha, R. Huin, H. Van Landeghem and A. Vidal, May 1973

Continuous regeneration of catalytic reformers offers an economical way to high octanes and high stream factors. New units can be designed to which continuous regeneration is added later.

Which heat recovery system?

A. Mol, July 1973

Check these pros and cons when selecting integrated vs. central waste heat recovery systems for ethylene plants.

How stable is diesel in storage?

M. E. LePera and J. G. Sonnenburg, September 1973

Present specifications may be inadequate to assure suitable diesel fuel storage stability. Laboratory tests are compared with actual 2-yr storage to judge a more suitable specification.

Polybutylene—New isotactic polymer

October 1973

Polymerizing butene-1 using Ziegler-Natta catalyst to crystallize polybutylene makes a unique polymer with interesting and useful physical properties.

How to design a plant firewater system

A. M. Woodard, October 1973

Industries that process large quantities of highly flammable fluids must be protected by well-designed and properly installed firewater systems. This article provides the fundamental design criteria that must be considered. Included are layouts showing a typical process unit fire protection system and a firewater pumping station.

How to improve compressor operation and maintenance

H. M. Davies, January 1974

All centrifugal compressors have their own operating and maintenance problems. However, these machines can be designed and built with operation and ease of maintenance in mind. This article will provide what to consider when selecting a new compressor.

Create by talking with a compute

G. E. Nevill, Jr., R. A. Crowe and J. R. Charles, Jr., March 1974

Tie a digital unit to a terminal, program it with the right words—then converse with it. The result is an aid to innovation in which the computer guides process, and the user implements ideas.

How to apply electric motors in explosive atmospheres

R. L. Nailen, February 1975

Equipment and personnel safety demands consideration of all the facts when an electric motor is to be operated in a hazardous plant environment. This articles provides guidelines that will help avoid many application errors.

LNG goes worldwide

J. D. Wall, April 1975

Continuing planning for new projects is expanding and enlarging the role of LNG in the HPI. Many projects are being considered, most of which are very involved in scope.

Ways to hydroprocess resids

A. G. Bridge, J. W. Scott and E. M. Reed, May 1975

Residuum processes are compared to show hydroprocessing is a commercially vialbe way obtain best liquid yields while meeting modern environmental criteria. Special consideration is given to residual desulfurization and vacuum gasoil/vacuum residual desulfurization for making low-sulfur fuel oils.

Reduce relief system costs

T. W. Whelan and S. J. Thomson, August 1975

The best way to develop an economical relief system design combines a computer program for engineering calculations and applied judgment on realistic relieving quantities.

Startup of a sour gas plant

D. L. Talley, April 1976

Everyone has trouble when they startup a new plant. How they handle the trouble is interesting and educational for all who must do the same thing. This article details Exxon's results in starting up a new gas recovery treating and sulfur recovery system.

From refining to coal gasification: New steels for fuel processing

R. A. Lula, June 1976

New ferritic stainless steels and austenitic steels with higher alloy content have promising corrosion resistant properties for oil refining and coal processing.

Recover energy with exchangers

J. B. Fleming, H. E. Duckham and J. R. Styslinger, July 1976

There are useful ways to curtail the consumption of excessive energy in heat exchanger operation. This article details an engineer/constructor's view of the design and application of these essential pieces of equipment and how operating companies can use them to their advantage.

Use infrared scanning to find equipment hotspots

T. Norda, January 1977

Safer and economical operation of most HPI plant equipment can be achieved by applying infrared inspection techniques.

Licensing—Present developments

G. Cramer, March 1977

International licensing, formerly a single agreement between private enterprises, has become entangled with politics. Licensing must return to straightforward economics and recognition of patent, trademark, contract and antitrust law.

Make the flare protect the environment

J. F. Straitz, October 1977

Eliminating waste gases is a special problem for environmental protection that can be solved by proper design and operation of flares. This article features an expert's opinion on this challenge.

Ether ups antiknock of gasoline

G. Pecci and T. Floris, December 1977

Methyl-tert-butyl ether can increase the antiknock ratings of gasoline blends. This article examines how the ether is made and what it can do.

Maintenance management for today's high-technology plants

H. F. Finley, January 1978

More complex equipment is entering HPI plants. Proper maintenance management will be required to keep it running economically. How can management cope with the maintenance requirements of higher technologies?

Use a matrix for project plans

R. L. Kimmons, February 1978

Six words form the essence of knowledge needed: What, why, when, how, who and where. Using these, a solid framework for the matrix can be developed.

Behavior of LPG on water

R. C. Reid and K. A. Smith, April 1978

Accelerated interest in the movement of LPG makes it important to understand the safety hazards related to spills, especially those occurring on water. This article provides tests to show what to expect.

More ways to use hydrocracking

A. Billion, J. P. Franck, J. P. Peries, E. Fehr, E. Gallei and E. Lorenz, May 1978

Various feedstocks of vacuum distillates and residues are explored with different catalyst systems to show the range of hydrocracking operation.

Latest clean air requirements

R. W. Dunlap and M. R. Leland, October 1978

New regulations under amendments to the U.S. Clean Air Act make it more difficult to obtain permits for new or expanded plants. This article defines and examines the major regulations that must be met.

How to apply programmable controllers

V. J. Maggioli, December 1978

New programmable controllers are designed to do more than just replace relays. This article shows how to maximize their capabilities by proper process definition, hardware and software selection, and safety and startup considerations.

LC-Fining upgrades heavy crudes

R. P. Van Driesen, J. Caspers, A. R. Campbell and G. Lunin, May 1979

The use of the LC-Fining process for upgrading heavy crudes has been evaluated in pilot plant tests and found effective in making it suitable for pipeline movement and refining in typical refineries.

Alcohols as a motor fuel?

J. L. Keller, May 1979

Methanol and ethanol are reviewed as alternative and supplement fuels for automobile engines.

Online computer optimization

P. R. Latour, June 1979

A burst of activity is underway to implement closed-loop steady state optimization for crude units, cat crackers, refinery distillation and many others. Presented in this article are the concepts of optimization, the mathematical techniques used and places where it really pays off for a variety of HPI processes.

A look at FCC catalyst advances

J. S. Magee and R. E. Ritter, September 1979

Changes in cracker design and catalyst formulation have evolved into an era of high product selectivity and reduced process emissions. This review identifies major catalysts changes.

Visbreaking: Low cost next step

M. Notarbartolo, C. Menegazzo and J. Kuhn, September 1979

To increase the yield of light products, a refiner should consider adding a visbreaking unit. Idle topping can be revamped to visbreaking.

How finance impacts profitability

J. L. James and P. R. Martin, December 1979

Cash flow has a dramatic influence on the money to be made from a project, and on the project schedule. This case history shows how to create an economic model for the role of capital in construction. HP

LEE NICHOLS, VP, Content/Editor-in-Chief

The 1980s: Oil spike/collapse, liquid crystals, conducting polymers and the rise of AR/VR

Several major impactful events took place in the global oil and gas and petrochemical industries in the 1980s. Nations around the world were hit with another spike in global oil prices, followed by a price collapse. This third crisis in 15 yr led many nations to invest in finding alternative fuels and/or feedstocks to produce transportation fuels and petrochemical products, including the discovery of a new coal gasification technology for chemicals production. The discovery of liquid crystals and conducting polymers not only created new fields of research, but also advanced the creation of a new host of electronic display devices and led to a Nobel Prize in Chemistry.

The 1980s also witnessed a greater focus on mitigating vehicle emissions and the continued phase-out of lead in transportation fuels. For example, the U.S. Environmental Protection Agency enacted a new standard in the mid-1980s to severely limit lead content in gasoline. The standard, enacted in 1986, decreased lead content in gasoline from 1.1 g/gal to 0.1 g/gal.[180] U.S. refiners also began to increase the use of methyl tertiary butyl ether (MTBE) in gasoline. MTBE was used as a replacement for tetraethyllead as an anti-knocking agent (i.e., octane enhancer).

Regions such as Asia and the Middle East experienced sizable increases in refining and petrochemicals production capacity during the decade. For example, the Middle East's refining capacity increased from 3.5 MMbpd in 1980 to more than 5.6 MMbpd in 1990.[181] Saudi Arabian petrochemical producer SABIC increased petrochemical production capacity by more than 6 MMtpy to 13 MMtpy by 1990 (this included the launch of several JVs, including KEMYA, YANPET, PETROKEMYA, SADAF and SHARQ)—the creation of SABIC, as well as the construction of Al-Jubail and Yanbu industrial cities and the country's master gas system, would propel Saudi Arabia to be the leading petrochemical producer in the region (these events were detailed in the 1970s history section). The Asia-Pacific region's net refining capacity expanded more than 1 MMbpd to more than 13.6 MMbpd from 1980–1990 (Japan's refining capacity declined more than 1.3 MMbpd in the 1980s).[181] The region's largest refining capacity increase occurred in China, which added nearly 1.2 MMbpd in the 1980s. China was followed by India, which added more than 560,000 bpd; Indonesia doubled domestic refining capacity to nearly 950,000 bpd in the same period.

The decade also witnessed the creation of three novel heavy-oil upgrading technologies, the popularization of new digital technologies that would enhance multiple facets of the oil and gas and petrochemicals industries in the future, and notable industrial accidents and ensuing directives that led to enhanced safety regulations still in use today.

A spike, an oil glut and a collapse. In the 1970s, two major oil crises—the oil embargo of 1973 and the oil crisis of 1979—significantly affected importing nations (both crises were detailed in the 1970s history section). The oil embargo of 1973 led to a quadrupling of oil prices globally and was an impetus for oil importing nations to intently focus on energy security. The embargo also led to the creation of the International Energy Agency in 1974 as a way for major energy consuming nations to discuss energy policies and strategize pathways for the security of supplies.[182]

The oil crisis of 1979—caused by the Iranian Revolution, which led to a sizable increase in global crude oil prices—had lingering effects into the early 1980s. The year-long revolution was responsible for knocking approximately 4.8 MMbpd of oil production offline. Although this represented only 7% of the world's oil production at the time, it led to global oil prices nearly doubling to \$39/bbl (equates to nearly \$140/bbl in today's currency after adjusting for inflation).[140]

As oil prices skyrocketed, oil producers swiftly ramped up production and fought for market share. Led by OPEC-producing countries, global crude oil production reached nearly 64 MMbpd in 1979–1980. However, a global economic recession from 1980–1983 led to a steep decline in oil consumption. Many industrialized nations (e.g., Canada, Japan, West Germany, the UK and the U.S.) witnessed high inflation rates and unemployment during this period. With oil production having ramped up over the past few years, the world was awash in oil, leading to a global glut that sent oil prices on a freefall.

During this timeframe, newly-elected U.S. President Ronald Reagan deregulated the U.S. oil and gas industry through executive order by removing price controls on gasoline, propane and U.S.-produced crude oil.[183] Although the policy helped reduce high pump prices and put market forces at the helm of crude oil and products pricing, it removed several beneficial incentives for smaller U.S. refiners. According to the U.S. Energy Information Administration, this led many small, simple refiners to shut operations. From 1980–1990, operable refineries in the U.S. decreased from nearly 320 to just over 200.[183] Most of these closures were within 2 yr after the decontrol of the U.S. oil and gas industry. This led the country's remaining refineries to expand

operations and invest in increasing processing complexity.

To mitigate wild fluctuations in crude oil prices, OPEC tried to stabilize the market by implementing production cuts. The OPEC London agreement of 1983 was a notable action taken by the cartel to try and prevent a crude oil price collapse (**FIG. 1**). The agreement contained two important accords: OPEC lowered the benchmark price of its light crude oil by \$5/bbl to \$29/bbl and agreed to cut production rates.[184] This was a historic occasion, as it was the first time that the cartel had lowered oil prices. By 1985, global oil production had declined from nearly 64 MMbpd in 1980 to less than 57 MMbpd.[185]

However, many OPEC nations disregarded agreed-upon production cuts and began to increase production rates. In late 1985, tired of trying to stabilize the oil market, Saudi Arabia boosted oil production, flooding the already oversupplied market. By March 1986, the tremendous spike in crude oil supplies led to prices collapsing to \$10/bbl—adjusted for inflation, prices collapsed from nearly \$140/bbl in early 1980 to nearly \$27.50/bbl in 1Q 1986.[186,187] Within a 15-yr timespan, the world had experienced three major oil price crises. It would not be for several years afterwards that the global oil market would fall into balance. However, it would not be the last oil price collapse or spike the global oil market would see. Several other significant price swings would occur over the next 30 yr.

FIG. 1. OPEC's extraordinary meeting in London in 1983 to try and stabilize the global oil market. The outcome of the meeting became known as the OPEC London agreement of 1983. Photo courtesy of OPEC.

FIG. 2. View of Eastman Chemicals Co.'s Kingsport plant in Tennessee (U.S.), the site of the company's proprietary coal gasification process. Photo courtesy of the American Chemical Society.

A new coal gasification process. Due to the effects of the oil crises in the 1970s (especially the oil embargo of 1973), several nations conducted extensive research on finding alternative energy sources to produce fuels and chemicals besides using crude oil as a feedstock. The stark increase in crude oil prices significantly increased both refiners' and petrochemical producers' feedstock costs—most petrochemicals produced at the time used oil-derived feedstocks; the same is true today.

In an effort to wean off using high-priced petroleum feedstocks for fuels and chemical products production, several companies set their sights on coal gasification and coal liquefaction technologies. Since coal was a cheap commodity, converting it into transportation fuels and/or using it as a feedstock for petrochemicals production looked to be a viable alternative vs. using high-priced crude oil. Coal gasification/liquefaction technologies were not new at the time. Technologies such as the Bergius process and Fischer-Tropsch process had been around for decades. Countries with abundant supplies of coal reserves could make use of existing coal gasification/liquefaction technologies to not only produce fuels and petrochemicals at a cost-effective rate, but also strengthen domestic energy security.

As global oil prices stabilized, many efforts to switch to other feedstocks fizzled out.[188] Conversely, the Eastman Chemical Co. continued research and development on coal-derived chemicals production. Like many chemical companies in the 1970s, Eastman was heavily dependent on crude oil and natural gas to produce petrochemicals. However, the company's petrochemical facility in northeast Tennessee (U.S.) was in close proximity to vast coal reserves in the Appalachian region of the eastern U.S.[189]

In the mid-1970s, Eastman conducted extensive research on utilizing coal to produce chemicals, especially acetic anhydride. At the time, the company consumed more than 1 Blb/yr of acetic anhydride to produce various products. Acetic anhydride was first synthesized by French chemist Charles Frédéric Gerhardt in 1852; it is used to produce acetate fibers, plastics, coatings and film.[189,190,191] The company began pilot plant operations in 1977, followed by construction and operations on a commercial facility in 1980 and 1983, respectively.

According to literature,[189] the facility used several different technologies to produce acetic anhydride from coal. Synthesis gas was produced using the Texaco Coal Gasification Process. The proprietary coal gasification technology would eventually be licensed by ChevronTexaco after the companies merged in 2001. It fell into the hands of GE Energy after the company purchased ChevronTexaco's gasification business in 2004. Air Products became the current owner of the technology after purchasing the GE gasification business in 2018.[192,193]

According to literature,[189] the coal gasification process used oxygen and coal/water slurry as feedstock for a gasifier, which used high temperature and pressure to produce two gas streams: shifted gas and raw synthesis gas. The two product gas streams left the gasifier and were purified—hydrogen sulfide (H_2S) and carbon dioxide (CO_2) were removed via the Rectisol process (licensed by Linde and Air Liquide). The H_2S was converted to elemental sulfur in a Shell Claus offgas treating unit, while the CO_2 was recovered and sold to make carbonated beverages.[186] The purified raw synthesis gas was cryogenically separated into hydrogen and carbon monoxide, with hydrogen used for methanol production and the carbon monoxide used for acetic anhydride production.[189] The final step used an Eastman proprietary reactive distillation process and catalyst system to produce acetic anhydride—purified carbon monoxide reacted with methyl acetate to form acetic anhydride.[189] In May 1983, operations began at the Kingsport plant (**FIG. 2**), which became the first U.S. facility to use a novel coal gasification process to produce a modern generation of industrial chemicals.[189]

Liquid crystals and conducting polymers. For more than 30 yr, electronic providers have produced items such as cell phones, personal computers/laptops and televisions with ever-increasing ultra-

clear displays. These technologies would not be possible without the advancement of liquid crystal polymers technology.

Although first discovered in the late 1800s by Austrian botanist and chemist Friedrich Reinitzer, liquid crystals did not find commercial success until nearly 100 yr later. In the late 1880s, Reinitzer was experimenting with cholesteryl benzoate. While heating the organic chemical, he noticed that it changed from a white solid to a hazy liquid, which then turned clear at higher temperatures. According to literature, Reinitzer observed that the liquid passed through two different color forms before returning to the original white solid form. Reinitzer concluded that the substance passed through two different melting points, which should not exist—German chemist Wilhelm Heintz observed the same phenomenon while conducting similar experiments on fatty acids in the mid-1850s.[194]

Reinitzer sent his findings to German physicist Otto Lehmann. Upon heating the material, Lehmann viewed the reaction under a microscope. As the solid changed into a milky liquid, Lehmann observed multiple small crystalline formations with irregular borders.[194] After additional testing and review, Lehmann believed this phase was a new state of matter, one between a solid and a liquid. He named the substance liquid crystals and published his findings "About floating crystals" in Zeitschrift für Physikalische Chemie (*Journal of Physical Chemistry*) in 1889. This was the first publication on liquid crystals.[195]

However, no commercial applications were discovered using liquid crystals. It was not until the late 1940s that extensive research began to be conducted on liquid crystals applications for commercial endeavors. This included works from the following references described in literature:[196]

- English researcher George William Gray: His book *Molecular Structure and the Properties of Liquid Crystals* provided a detailed understanding on designing molecules that exhibit the liquid crystalline state. His work would be instrumental in the future adoption of liquid-crystal displays (LCDs).
- American chemist Glenn H. Brown: His liquid crystals conference in the mid-1960s gathered the world's most-prominent scientists on the subject and was a catalyst for worldwide research efforts on the advancement of liquid crystals technologies research.
- Richard Williams and George Heilmeier: Their work at RCA Laboratories in the U.S. in 1962 were the origins of using a liquid crystal-based flat panel display to replace the cathode ray vacuum tube used in televisions. However, to be used effectively, the compound used in the process (para-azoxyanisole) to create a nematic liquid crystal state required too high of a temperature (> 116°C) to make it a practical application for television displays. In 1966, while working within the Heilmeier group, Scientists Joel Goldmacher and Joseph Castellano were able to create nematic liquid crystals at room temperature by altering the compounds used in the process. This enabled RCA to produce the first practical display device.

In 1972, George Gray and Ken Harrison worked with the Royal Radar Establishment in Malvern, England to produce stable liquid crystals for small LCDs within electronic products.[196] Additional research in the 1980s led to an extensive use of liquid crystal polymers in display devices (i.e., LCDs for television, mobile phones, personal computers and laptops) and other products within the automotive, electronics and medical sectors. Today, many companies produce liquid crystal polymers (e.g., Celanese, Polyplastics, Solvay, Sumitomo Chemicals and Toray Industries), and forecasts show the liquid crystals polymers market to reach nearly $2.5 B by 2030.[197]

Conducting polymers. Prior to the 1970s, it was a common belief that plastics could not conduct electricity. However, research by three scientists changed the fundamental thought on the conductivity of polymers. This research would not only lead to the production of many different products for various industries, but also earned these men the Nobel Prize in Chemistry.

Conductive polymers are organic polymers that conduct electricity.[198] Research and discovery of partly conductive polymers date back to 1862. While working at the College of London Hospital, English chemist Henry Letheby obtained a partly-conductive material by anodic oxidation of aniline in sulfuric acid.[199] Additional research in the 1970s found that polythiazyl (polymeric sulfur nitrade) was superconductive at low temperatures, while several other conductive organic compounds were superconductive at high temperatures.[199]

In the early 1970s, Japanese chemist and engineer Hideki Shirakawa led a group that adapted Ziegler-Natta polymerization to produce well-defined, silvery films of polyacetylene (the work of Karl Ziegler and Giulio Natta is detailed in the 1950s history segment).[199,200] During the same timeframe, American physicist Alan Heeger and New Zealand-born American chemist Alan MacDiarmid were researching the metallic properties of polythiazyl. The two scientists shifted their focus to polyacetylene after MacDiarmid met with Shirakawa in Tokyo.

In 1976, MacDiarmid, Shirakawa and Heeger (**FIG. 3**) collaborated on addi-

FIG. 3. MacDiarmid, Shirakawa and Heeger were awarded the Nobel Prize in Chemistry in 2000 for their work on conductive polymers. Photo courtesy of the Nobel Foundation archives.

tional research focused on the conductivity of polyacetylene. In 1977, additional experiments showed that doping polyacetylene with iodine increased its conductivity by seven orders of magnitude; similar results occurred using chlorine and bromine, as well. The trio published their findings in the article "Synthesis of electrically conducting organic polymers: Halogen derivatives of polyacetylene, $(CH)_x$,"[201] followed by two separate deeper dive articles into the technical research and conclusions of their work.

The efforts of MacDiarmid, Shirakawa and Heeger were instrumental in creating a new field of plastic electronics research, which gained prominence in the 1980s and led to numerous products and applications. These included antistatic substances for photographic film, shields for computer screens and smart windows that absorb sunlight, light-emitting diodes (LEDs), solar cells, displays in mobile phones and small television screens, batteries, specialty coatings, and many other applications.[198,202] For their contributions in the field of conducting polymers, MacDiarmid, Shirakawa and Heeger were awarded the Nobel Prize in Chemistry in 2000.

From tragedy to a safer industry. Notable industrial accidents occurred in the mid-1970s through the 1980s that led to stark changes in the way industry views safety. These included the Bhopal and Seveso disasters and the Phillips 66 Houston Chemical Complex explosion.

In July 1976, a chemical leak at a small chemical plant north of Milan, Italy exposed the surrounding region to high levels of 2,3,7,8-tetrachlorodibenzo-p-dioxin. The leak severely affected humans, wildlife and the environment. It was later determined that the plant had very rudimentary safety systems, it had not considered environmental protection during construction/operation and had no warning system or health-protection protocols for the surrounding communities.[203]

The Seveso disaster led to the adoption of the Seveso Directive in 1983. The directive (82/501/EC) aims to control major accident hazards involving dangerous substances, especially chemicals, and contributes to the technological disaster risk reduction effort.[204] The directive was superseded by Seveso 2 (1996)—also referred to as Control of Major Accident Hazards (COMAH)—and Seveso 3 (2012). These amendments were the results of other industrial accidents that severely affected surrounding populations and the environment. The major takeaways from the Seveso Directives were the obligations placed on plant operators, which included mandatory safety reports, the establishment of a detailed safety management system and emergency action plans, and the deployment of major accident prevention policy, among others.[205] Today, the Seveso Directive applies to more than 12,000 industrial establishments in the EU and is widely considered a benchmark for industrial accident policy for nations around the world.[204]

Two other major industrial accidents in the 1980s changed the way the industry views process safety management: the Bhopal disaster and the Phillips 66 chemical plant explosion. The Bhopal disaster occurred in the late evening/early morning of December 2–3, 1984 in Bhopal, India. Shortly after midnight on December 3, up to 40 t of toxic methyl isocyanate leaked from the plant's storage tank and drifted downwind into the surrounding community.[206] The highly toxic material claimed the lives of thousands of people and resulted in more than 550,000 injuries.

The Bhopal tragedy led to new safety and environmental measures and government regulations in India. This included the Environmental Protection Act of 1986, which created the Ministry of Environment and Forests—the ministry was responsible for enforcing environmental laws and policies. It also led to the Factories Act of 1987; the Hazardous Wastes (Management and Handling) Rules; and the Manufacture, Storage and Import of Hazardous Chemical rules, both enacted in 1989, among other rules and regulations.[207] The Bhopal disaster also influenced the Seveso 2 amendment in Europe and raised awareness from governing bodies around the world that enhanced safety management systems were needed in industry.

In the mid- to late-1980s, several governmental safety organizations proceeded with advancing new safety management system regulations. For example, the Occupational Safety and Health Administration (OSHA) in the U.S developed the process safety management system regulation in the late 1980s. The regulation—still in use today—focuses on the handling, manufacturing, storage and onsite movement of highly hazardous chemicals.[208]

However, new regulations in process safety management in the U.S. were still a work in progress when an explosion happened at the Phillips 66 high-density polyethylene plant in Houston, Texas (U.S.). The series of explosions—caused by the release of flammable process gases that contacted an ignition source—on October 23, 1989, claimed the lives of nearly two dozen and resulted in hundreds of injuries.[209] The tragedy increased the focus on better process safety systems in dangerous work environments, especially in the refining and petrochemical industries. According to literature, several insights prevailed in the aftermath of the accident, including a better adherence to safe work practices and a better overall process safety and risk management program, the creation and adoption of new standards and regulations, the detrimental effects that can occur when safeguards are removed or disabled, and the need for operational discipline in plant operations.[210]

Unfortunately, the three industrial accidents mentioned here were not the last to occur within the processing industries. However, these major industrial tragedies led to an increased focus on process safety management at both refineries and chemical plants. They have left a lasting impression and have been responsible for new directives, standards and safety guidelines throughout the processing industries in an effort to keep plant personnel and surrounding communities safe.

Heavy oil upgrading. In 1984, the Association for the Valorization of Heavy Oils (ASVAHL) was assembled in France. The ASVAHL Analytical Group was comprised of the Institut Français du Pétrole [French Institute of Petroleum (IFP), which would later take the name IFP Energies nouvelles], Elf Aquitaine (a French petroleum and natural resources group that was acquired by Total Fina in 2000 and is now Total Energies)[211] and Total (now Total Energies).

The group's primary function was to research and develop new heavy-oil upgrading technologies. According to literature, the group's main objectives included developing straightforward methods for the conversion of heavy products and a better knowledge of the structure of heavy products.[212]

ASVAHL's research and findings led to the development of three major heavy-oil processing technologies: Hyvahl, Solvahl and Tervahl. The Hyvahol technology is a fixed-bed residue desulfurization process that enables refiners to produce ultra-low-sulfur fuel oil and low-sulfur diesel—the process is now licensed by Axens (the company was created by IFP in mid-2001 through its merger with Procatalyse Catalysts and Adsorbents).[213,214] The Solvahl technology (also licensed by Axens) is a solvent deasphalting process that removes asphaltenes, most metals and other impurities contained in atmospheric or vacuum residues.[215] Tervahl is a residue and heavy-oil conversion process by using thermal cracking.[216] These heavy-oil processing technologies are still in use today.

The rise of virtual/augmented reality: A precursor to the digital transformation. The 1980s not only witnessed the beginning of the rise in video gaming systems (Atari and Nintendo rose to prominence in the decade)—a market that would reach nearly $200 B in 2021—but also in the popularization of virtual reality (VR).[217]

One of the earliest VR systems was the Sensorama created by Morton Heilig in the mid-1950s. This "theater" included a stereoscopic color display, fans, odor emitters, a stereo sound system and a motion chair.[218] The mechanical device would use sights and sounds to simulate reality for the viewer. Heilig followed up his Sensorama invention with the telesphere mask in 1960 (**FIG. 4**). This mask was the first iteration of a head-mounted display (HMD) device for VR and is a rudimentary version of the HMDs available in consumer and industrial markets today.

In 1969, Myron Krueger created computer-generated environments that responded to the user. This system eventually progressed, leading to the creation of VIDEOPLACE. According to literature, this virtual world could analyze and process the user's actions in the real world and translate them into interactions with the system's virtual objects.[219] Krueger eventually termed this type of system "artificial reality."

Both VR and artificial reality [also known as augmented reality (AR)] research and development increased exponentially over the next several decades.

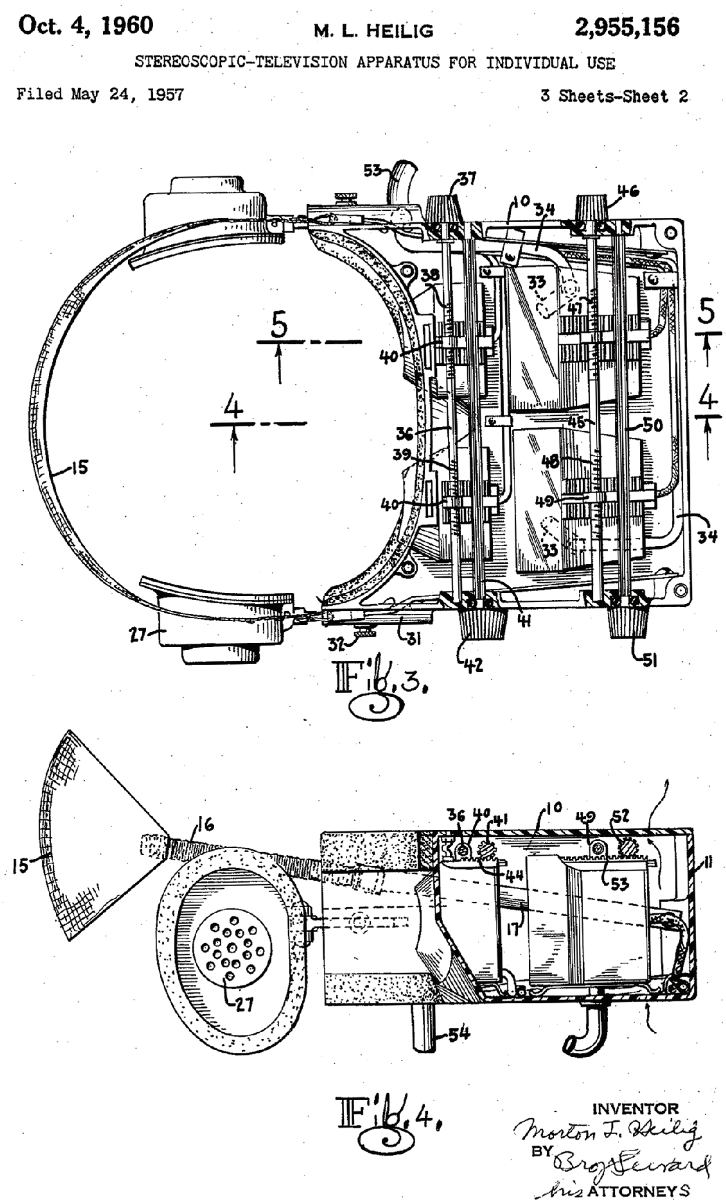

FIG. 4. Drawings of Heilig's telesphere mask from his patent Stereoscopic-Television Apparatus for Individual Use. Source: U.S. Patent Office, patent no. 2,955,156.

For example, many advances in AR/VR technologies happened in the 1980s. These included the creation of Sayre gloves that used optical sensors to detect finger movements, the creation of VPL Research by Jaron Lanier and Thomas Zimmerman (the company was the first to sell HMDs and gloves to consumers, and Lanier was the first to coin the term "virtual reality"), advanced flight simulators for pilots, and VR to train National Aeronautics and Space Administration (NASA) astronauts, among many others.[220]

Today, AR and VR are advancing technologies within the oil and gas and petrochemical sectors, primarily due to the industry's digital transformation. HPI professionals utilize AR/VR technologies for training, maintenance, planning, safety, engineering and design. The advancements in AR/VR systems are enabling the HPI to digitally enhance operations and safety throughout all sectors of the oil and gas and petrochemicals industries. The adoption of these technologies is forecast to increase the AR/VR market in the oil and gas industry to nearly $1 B by 2027.[221] HP

LITERATURE CITED

Complete literature cited available online at www.HydrocarbonProcessing.com

LEE NICHOLS, VP, Content/Editor-in-Chief

Excerpts from the 1980s: Energy efficiency, advanced process controls, improved maintenance and a focus on the environment

Can a computer reduce your maintenance?

J. H. Redding, January 1980

How do computers reduce costs and improve operations? What are some of the limitations? How do you justify a computer system? How large should your system be? These questions are answered here.

How to select hydrotreating catalyst

T. F. Kellett, A. F. Sartor and C. A. Trevino, May 1980

A comparison between cobalt/molybdenum (Co/Mo) and nickel/Mo (Ni/Mo) catalyst shows applications for desulfurization, denitrogenation and hydrogen uptake. Specifics are given for Shell catalysts to emphasize differences.

Make olefins from syngas

V. U. S. Rao and R. J. Gormley, November 1980

This catalyst of silicalite impregnated with iron and promoted with potassium has an exceptionally high selectivity for producing C_2–C_4 olefins from synthesis gas.

Chemicals from methanol

M. B. Sherwin, March 1981

Current and developing chemical synthesis based on methanol indicate dramatic demand growth as a feedstock.

How to evaluate distributed computer control systems

S. Cocheo, June 1981

Control systems and process engineers are faced with a wide variety of distributed systems to choose from. Which vendor's offering is best for each plant? Here are the factors the engineer must understand and evaluate to make a proper selection.

Better use of refining energy

D. J. Ducote and R. Ragsdale, September 1981

If you are not trying to save energy, maybe you should be. Here are some ideas for energy savings in the hydrocarbon processing energy.

Stop emissions from liquid sulfur

J. A. Lagas, October 1982

Serious environmental and safety problems can arise in the handling of liquid sulfur. Fatal levels of hydrogen sulfide (H_2S) can accumulate in the vapor spaces above the sulfur—or even flammable levels. Here is the story and how to handle the problem.

Convert to microprocessor controls without shutting down

M. E. Leister and R. R. Sanders, April 1983

Here is how this refinery converted 12 units (3,000 loops) to microprocessor-based controls without a process shutdown.

Convert steam balances into dollar balances

W. V. L. Campagne, June 1983

Use this method to determine the real value of steam, condensate and brake horsepower.

What is cogeneration effectiveness?

M. P. Polsky and R. J. Hollmeier, July 1983

Several evaluation methods of cogeneration effectiveness are analyzed, and their strengths and weaknesses presented.

How to upgrade heavy feeds

B. Schuetze and H. Hofmann

Refiners have many options for converting heavy black oil to light white oil. Here is a review of the choices.

Integrate gas turbine cogeneration with fired heaters

G. Iaquaniello, S. Guerrini, P. Pietrogrande and H. Dreyer, August 1984

Heat and power cogeneration is a potentially rewarding technique for achieving energy savings when applied to process industry systems. This article presets an innovative solution which can improve the efficiency of large petrochemical plants and refineries.

Make phthalic anhydride with a low-air-ratio process

L. Verde and A. Nari, November 1984

A new catalyst permits cutting the air ratio in half and reduces investment in energy consumption. This article features a novel proprietary process to produce phthalic anhydride.

Basics of fire protection design

J. D. Soden, May 1985

Most hydrocarbon processing facilities have an inherent potential for fire from materials and from processes and reactions being conducted. Little can be done to reduce or eliminate this potential. Fire safety design, therefore, addresses reducing the probability of fire occurrence (preventive design) and minimizing the consequences should a fire occur (protective design).

Turbines lower NO_x emissions

F. Giacobbe, Y. Lee, P. Pietrogrande and G. Iaquaniello, October 1985

Combining gas turbine and conventional heaters for power and process use reduces pollution while making electricity and saving money.

What went wrong? Case histories

T. A. Kletz, December 1985

Murphy's Law: "If anything can go wrong, it will." To prove the point, here are examples of HPI losses and what can be done to prevent them.

Selecting your next MMA process

R. V. Porcelli and B. Juran, March 1986

Technological changes and end-use developments will affect the next round of methyl methacrylate (MMA) plants.

Career success and your self-image

E. Raudsepp, March 1986

Here is a step-by-step walkthrough of what it takes to be successful in your career, and a profile of failure patterns that damage career progress.

Special Report: Gas Process Handbook

April 1986

This complete review of processes for operations includes natural gas, sulfur, hydrogen, flue gas and cleanup, liquids treating, gasification, shift and methanation, and C_3–C_5 conversion.

AI and MAP in the processing industries

L. A. Kane, June 1986

Here are the principles of artificial intelligence (AI) and manufacturing automation protocol, and examples of their use in the processing industries.

Redesign catalyst to save energy

J. A. Russell, S. E. Lyke, J. K. Young and J. J. Eberhart, July 1986

Theoretical limits show the energy savings found when a catalyst is designed for optimum operation of a catalytic cracking unit.

How refinery inventories threaten profitability

G. M. Intille, July 1986

Inventory control may be second only to fluctuating crude oil prices in its potent challenge to refinery managers.

Use performance indices for better control

V. A. Bhandari, R. Paradis and A. C. Saxena, September 1986

Would it not be easier to control fuel usage in your automobile if it had a gauge that showed miles/gallon or kilometers/liter? Here is how to use your distributed control system (DCS) to do the same thing for your processes.

Avoid self-priming centrifugal pump problems

G. G. Reeves, January 1987

Design and installation guidelines ensure that horizontal self-priming centrifugal pumps operate correctly.

How construction affects column control

P. Mizsey, H. Hajdú and P. Földes, February 1987

In the development of control strategies for distillation columns and absorbers, generally no attention is paid to the construction parameters and the type of built-in trays of the column. This article compares the responses of various trays to flow disturbances to show how column control is affected.

Europe's future gasoline options

May 1987

Legislative limits on engine emissions and fuel properties have severe consequences for Europe's cars and fuels. Estimates are given for refining options.

Include tech service engineers in turnaround inspections

J. E. Miller, May 1987

Startup problems can be reduced because of the unique perspective that process and technical service engineers have on equipment operation. Here is how to include them.

Advanced Process Control Handbook

March 1988

More than 100 strategies for advanced control of refining, gas processing, petrochemical and utility processes are presented. To make the handbook more complete, the best of previously published control strategies are included in abbreviated form without diagrams. New descriptions are presented with half-page diagrams so that more could be included.

Low-cost ammonia and CO_2 recovery

V. A. Shah and J. McFarland, March 1988

Using a low-energy CO_2 recovery process on the syngas intended for ammonia production results in an overall lower cost ammonia plant. Data are given to compare capital and operating costs.

Modern control tricks solve distillation problems

H. F. Bozenhardt, June 1988

Replacing old controls with a new DCS and implementing the advanced control algorithms described here provided a 2-mos payout on this azeotropic distillation column.

Ways to revamp urea units

F. Granelli, June 1988

Several factors should be examined when considering a revamp of a urea plant. Experience teaches which parts of the unit are likely to be involved.

Economics of new MTBE design

A. M. Al-Jarallah and A. K. K. Lee, July 1988

Methyl tertiary butyl ether (MTBE) is produced industrially by the catalytic reaction between methanol and isobutene. The catalyst that is widely used is an acidic ion exchange resin. This article explores design and economics when sulfuric acid is the catalyst.

Build an effective group for instrumentation systems

W. E. Fullen, August 1988

A skilled, experienced, efficient team is needed because of the advancement in recent years by microprocessing/electronics.

Magnetic bearings and dry seals improve compressor operation

J. Fort and J. Jehl, October 1988

An advanced oil-free compressor featuring active magnetic bearings and dry gas seals has been operating successfully for more than 7,500 hr. Here is a description of the project.

Better ethylene separate unit

V. Kaiser and M. Picciotti, November 1988

An ideal column concept guides improvements to ethylene plant gas separation. This results in better efficiency from limited investments.

Reduce olefin plant fouling

J. F. Martin, November 1988

Process-side fouling reduces the overall operating efficiency of an olefin plant. The fouling is commonly caused by the formation of organic polymers that can also contain small amounts of inorganic constituents. This article provides several case studies to show the results of effective remedies for fouling in various locations of the olefin plant.

Operational speed balancing: Should you be doing it?

L. Fisher, January 1989

Vibration is one of the primary enemies of rotating equipment and eliminating or lessening vibration can significantly improve operating efficiency and system longevity. Since a large portion of vibration problems in high-speed turbomachinery is due to an unbalanced motor, operational speed balancing of the rotor might achieve these objectives.

Refinery heat integration using pinch technology

K. L. Lee, M. Morabito and R. M. Wood, April 1989

Direct and indirect integration schemes for crude oil refining applications are compared using pinch technology procedures.

Data reconciliation: Getting better information

P. J. Lawrence, June 1989

Good data are essential to control and information systems. Here is how to use data reconciliation to improve instrumentation and corporate decision-making.

Bioremediation on the move

C. H. Vervalin, August 1989

The current frenzy in the HPI to meet groundwater protection needs is bringing with it some interesting developments in soil-contamination activity. For example, microbes with a taste for hydrocarbons can be grown to remove oily waste from dirt. These "bugs" promise to chew their way through some of the HPI's waste disposal problems. The future is not here yet, but it is coming.

Hydroprocess catalyst selection

C. T. Adams, A. A. Del Paggio, H. Schaper, W. H. J. Stork and W. K. Shifflett, September 1989

Flexibility in residuum hydroprocessing becomes a requirement as fuel oil demand weakens, crude slates tend to be heavier, and variability in crude oil cost and supply become the norm. One way of providing flexibility is to incorporate residuum hydrotreating ahead of a heavy-oil catalytic cracking unit that converts heavier components into lighter, more valuable products. Alternatively, significant conversion of the residuum to lighter products can be achieved by the operation of the residuum hydrotreater at a higher severity to facilitate hydrocracking reactions.

In both cases, the proper combination of catalysts for the desired feedstock selection and more of operation is critical for economic hydroprocessing operations. This article focuses on the design and selection of catalytic systems in the framework of a unified reactor modeling scheme for such residuum hydroprocessing applications.

Guidelines for rotating equipment

O. P. Goyal, October 1989

Engineers, designers and operators must know certain facts about rotating equipment process concepts, design aspects, operating needs and troubleshooting methods. Experience has shown that a list of selected guidelines makes their jobs more effective. In this article, guidelines are compiled for centrifugal pumps, centrifugal compressors, reciprocating compressors, electric motors and steam turbines.

HPI 1990 Outlook: A Special Report

December 1989

The HPI will spend \$117.5 B in 1990, with \$66 B earmarked for petrochemicals alone. Approximately \$18 B will go into maintenance. Capital expenditures are forecast at \$27.4 B, with around \$13.7 B being spent on equipment and materials. A construction boom is helping to drive the "big bucks" outlay.

Simulator trains for new equipment use

H. Elston and D. Potter, December 1989

This "stepping stone" approach to training operators uses a process simulator as one of the steps. Trainees adapt quickly, willingly. HP

LEE NICHOLS, VP, Content/Editor-in-Chief

The 1990s: Clean fuels and emissions mitigation, M&A, GTL and the fieldbus wars

Much like several initiatives passed in the 1970s and 1980s, the 1990s were a decade heavily focused on environmental issues, with many new regulations being enacted to not only mitigate industrial and vehicle emissions but also to advance the production of clean fuels globally. As a result, refiners spent billions of dollars during the 1990s to install, modify, upgrade and reconfigure process units to adhere to new government regulations [e.g., the establishment of the reformulated gasoline program (Phases 1 and 2) in the U.S.].[222] This trend is still progressing today. Additional greenhouse gas emissions reduction initiatives also emerged from the Kyoto Protocol in the late 1990s/early 2000s, a precursor to the Paris Agreement in 2016. Both agreements call upon nations to significantly mitigate carbon emissions.

New clean-fuels regulations led to additional refining capacity being built during the 1990s to reduce sulfur levels in transportation fuels. In conjunction with new secondary unit capacity builds, the refining industry increased total net crude distillation capacity by nearly 8 MMbpd, reaching more than 83 MMbpd by 2000.[181] Although rocked by an economic crisis in the late 1990s, the Asia-Pacific region led refining capacity additions, adding more than 8 MMbpd (net) by 2000—China alone more than doubled domestic refining capacity to nearly 6 MMbpd within the decade.[181]

The 1990s also witnessed the increased usage of metallocene catalysts. Metallocene structures were first discovered simultaneously in the 1950s by Thomas Kealy and Peter Pauson at Duquesne University (U.S.), and by a different group comprised of Samuel Miller, John Tebboth and John Tremaine at British Oxygen (now part of Linde) in London, England—these groups worked with ferrocene, a type of metallocene.[223, 224]

A commercial use for metallocene was discovered in the 1970s by German chemist Walter Kaminsky while working at the University of Hamburg (Germany).[225] According to literature, Kaminsky discovered that using metallocene with a methyl aluminoxane cocatalyst led to a novel pathway for olefin polymerization. This discovery led to many companies increasing their research and development budgets to produce new metallocene catalysts for polymer production (e.g., polyethylenes, polypropylenes, polystyrene). Many companies introduced proprietary metallocene catalysts in the 1990s, including ExxonMobil, Dow Chemical, BASF and Mitsui, among others.[226]

The 1990s also witnessed a surge in high-profile mergers and acquisitions, the advancement of gas-to-liquids (GTL) technologies and capital-intensive GTL plant builds, and the evolution of fieldbus technologies and the standards that govern them.

New fuel standards directives lead to a decline in sulfur content. One of the detrimental effects of modernizing societies is an increase in air pollution. Increased smog from fuel exhaust has been a challenge in many cities around the world for more than 70 yr. Many nations' governments have enacted a host of regulations and standards to combat air pollution. For example, the U.S. began to enact new air pollution laws in the mid-1950s. These directives led to the Clean Air Act and various amendments, which gave more authoritative power to the U.S. Environmental Protection Agency (EPA) to mitigate air pollution. These acts/amendments also created federal standards for vehicle emissions (the history of the Clean Air Act and subsequent amendments are detailed in the 1970s history section).

The Clean Air Act of 1990 led to the creation of tiered emissions standards for vehicles in the U.S. The Tier 1 standard was introduced in 1991 and phased into the market between 1994 and 1997. Tier 2 was adopted in 1999 and phased-in from 2004–2009.[227] The Tier 2 program marked the first time the U.S. EPA treated vehicles and fuels as a system.[228] These standards applied to light-duty vehicles (i.e., vehicles ≤ 8,500 lb) and led to a significant decline in sulfur limits in transportation fuels (gasoline and diesel). Prior to these regulations, on-road diesel fuel sulfur content was more than 5,000 parts per million (ppm). To adhere to new emissions standards put forth in the Tier 1 program, new low-sulfur diesel fuel was introduced into the market in the early 1990s. This fuel met the new sulfur limit specification of 500 ppm, significantly decreasing total sulfur content in diesel fuel.[229]

The Tier 2 standard helped reduce sulfur content in gasoline by up to 90%. By early 2004, the corporate average gasoline sulfur standard was 120 ppm, with a cap of 300 ppm. This standard was reduced to 30 ppm with an 80-ppm cap in 2006.[230] The Tier 2 standard also reduced sulfur content in diesel fuel to 15 ppm, which became known as ultra-low-sulfur diesel (ULSD). Subsequent regulations would further decrease sulfur content in fuels—the Tier 3 fuel regulation, adopted in 2017 with implementation to 2025, further reduced sulfur content in gasoline to 10 ppm.

In Europe, research by French and German scientists into smog mitigation in major cities in the mid-1950s led to the origins of new emissions standards

in the region. Their work led to Directive 70/220/EEC in 1970, which was the impetus to setting emissions standards for light- and heavy-duty vehicles in Europe (this research was detailed in the 1970s history section).[145] This directive eventually led to the introduction of the Euro 1 standard in 1992 (implemented for passenger cars in 1993), the removal of leaded petrol from filling stations in Europe and the adoption of three-way catalytic converters.[144,146,147] The Euro 1 standard was replaced by Euro 2 in 1996, which reduced sulfur limits in diesel from 2,000 ppm to 500 ppm; Euro 3, introduced in 1999 and implemented in 2000, further reduced sulfur content in diesel to 350 ppm and gasoline to 150 ppm. Subsequent standards (i.e., Euro 4–6 and Euro I–IV) would continuously reduce sulfur content in transportation fuels to near-zero levels.

The implementation of European emissions standards in the early 1990s would eventually become a global standard for many countries around the world to adhere to new clean fuels regulations. For example, more than a dozen Asian nations started using European emissions and fuel quality standards in the late 1990s/early 2000s. Many still use these standards as a benchmark for sulfur content in transportation fuels. The same initiatives apply in other regions, such as Africa, Central and South America, and the Middle East.[231]

These new sulfur cap limits in transportation fuels have had significant impacts on refiners globally. To produce fuels that adhere to these standards (e.g., Tier 3 in the U.S., Euro 6/VI in Europe and other parts of the world), refiners must invest a significant amount of capital in new secondary units. Since the adoption of emissions and sulfur content standards in the U.S., Europe and other nations, tens of millions of barrels per day in new secondary unit capacity have been built at a cost of hundreds of billions of dollars.

Consolidation in the oil industry: Mergers and acquisitions that created mega-companies. The 1990s witnessed several significant mergers and acquisitions that created some of the largest integrated companies in the world. Combined, these deals exceeded $220 B and included the following:

- **bp and Amoco:** In 1998, bp merged with Amoco in a more than $48-B deal, which was the largest industrial merger ever up to that point in time.[232] The merging of the two companies created an energy conglomerate with a market capitalization of $110 B. The deal was complementary for both sides. bp, through Amoco, strengthened its refining and chemicals production and products marketing—Lord Brown (bp's chief executive 1995–2007) said that through the merger, bp gained 9,300 fuel stations and five refineries that produced a total of 1 MMbpd.[233] By merging with bp, Amoco gained a foothold on the international market, a weak spot for the company at the time.
- **bp Amoco and ARCO:** Not even 1 yr after bp and Amoco merged, bp Amoco acquired the Atlantic Richfield Co. (ARCO) for $27 B. The acquisition significantly increased bp Amoco's foothold in Alaska's North Slope (U.S.) oil exploration and production operations, as well as captured 20% of California's (U.S.) fuels retail market—at the time, ARCO owned approximately 1,200 fuel service stations in the state.[234]
- **Total and Petrofina:** In 1998, Total acquired Belgian oil company Petrofina for $12 B. The deal created the third-largest company (TotalFina) in Europe, and the sixth-largest company in the world. The acquisition helped Total gain a more international foothold, increased the company's refining and products marketing operations, and provided the new organization (TotalFina) with a market capitalization of nearly $40 B.[235]
- **TotalFina and Elf Aquitaine:** Approximately 8 mos after acquiring Petrofina, TotalFina acquired Elf Aquitaine (Elf) for approximately $54 B.[236] At the time, Elf was a major integrated oil and gas company and one of the largest petrochemical companies in the world. TotalFina not only gained sizable exploration and production operations in West Africa and the North Sea from Elf, but also its petrochemicals and chemicals production capacity, five refineries and Elf's 6,500 fuel stations throughout Europe and West Africa.[237] After the merger was completed, TotalFina Elf became the world's fourth-largest company.[237]
- **Exxon and Mobil:** In 1998, Exxon announced an $81-B deal to merge with Mobil, which would create the third-largest company in the world behind General Electric and Microsoft.[238] The U.S. Federal Trade Commission (FTC) unanimously approved the merger in late 1999 dependent on the two organizations agreement to divest a sizable amount of assets. For example, the FTC ordered the two companies to sell more than 2,400 fueling stations in the northeast U.S., California and Texas; Exxon had to sell its refinery in Benicia, California, and agreed to stop selling gasoline and diesel fuel under the Exxon name in the state for 12 yr; and other assets. These demands from the FTC were the largest divesture ever asked by the commission up to that time.[239] The merger not only created a mega-company with a market capitalization value of nearly $240 B, but also reassembled two pieces of John D. Rockefeller's Standard Oil empire that was broken up in 1911.
- **Shell and Texaco:** In 1997–1998, Shell and Texaco agreed to a partial merger of downstream operations and fuel stations in the west and Midwest portions of the U.S. The JV, Equilon Enterprises, operated eight refineries, 10 lubricant plants, more than 70 oil and product terminals, and more than 11,200 fueling stations and convenience stores.[240] Equilon soon joined Saudi Refining (now Saudi Aramco) to create Motiva Enterprises, which eventually would operate one of the largest refineries in the world, the 630,000-bpd Port Arthur refinery in Port Arthur, Texas (U.S.). Shell would eventually retain all Equilon Enterprises and Texaco's share in Motiva to pave the way for Chevron and Texaco's $39-B merger in 2001.

Bintulu and Mossel Bay: The world's first GTL complexes. The first wide-scale use of synthetic fuels production from syngas was in Germany in the 1930s and early 1940s. These facilities utilized the Fischer-Tropsch (FT) process, a chemical reaction that converts carbon monoxide (CO) and hydrogen into liquid hydrocarbons (e.g., transportation fuels). According to literature, by the mid-1940s, Germany had nine plants in operation that used the FT process. Combined, these plants produced approximately 600,000 tpy of synthetic fuels.[241]

FT synthesis was the basis for several plants developed by Sasol in South Africa beginning in the mid-1950s. These included Sasol-1–3 plants, which used coal as the primary feedstock, later transitioning to natural gas in the early 2000s—Sasol developed and commercialized its Slurry Phase Distillate FT process at the Sasol-1 plant in Sasolburg, South Africa in the early 1990s.[242] Sasol-2 and Sasol-3 plants were built in the early 1980s as a direct effect of the oil crises of the 1970s—these plants accounted for $6 B in capital investments and utilized proprietary GTL technology from Sasol.[241]

Sasol's FT technology was then utilized for the Mossgas GTL plant, which, upon completion in 1992, became the world's first commercial-scale GTL plant using natural gas as a raw material for syngas production.[241] The Mossgas GTL plant, located in Mossel Bay, eventually fell into the hands of The Petroleum, Oil and Gas Corp. of South Africa (PetroSA)—the national oil company of South Africa—after its formation in 2002 upon the merger of Soekor, Mossgas and parts of the Strategic Fuel Fund Association.[243] The facility converts natural, methane-rich gas into high-value synthetic fuels. According to PetroSA, the technology uses a series of conversions starting with the reforming of methane to carbon dioxide (CO_2), CO, hydrogen and water. The CO-to-hydrogen ratio is adjusted using the water-gas shift reaction and the removal of excess CO_2 in an aqueous solution of alkanolamine. The synthesis gas is then chemically reacted over an iron or cobalt catalyst to produce liquid hydrocarbons (gasoline, kerosene, diesel) and other byproducts.[244]

The Mossel Bay GTL plant has been expanded over the past two decades, reaching a total installed capacity of 36,000 bpd—a crude oil equivalent of 45,000 bpd. Sasol has also improved its FT-GTL process, which was used for Sasol's second large-scale GTL plant, Oryx GTL. The Oryx GTL facility—a JV between Sasol and Qatar Petroleum—in Ras Laffan City, Qatar started development in 2003 and began operations in 2007. The 34,000-bpd plant was built at a total cost of nearly $1 B. Sasol would later provide its FT technology to Chevron for the nearly $10-B, 33,000-bpd Escravos GTL plant in Escravos, Nigeria, and the $3.4-B, 1.5-MMtpy Oltin Yo'l GTL plant in Uzbekistan.

Shell was another company that devoted significant resources to the development of a GTL technology and subsequent capital-intensive investments in new GTL processing capacity. In 1993, Shell commissioned its first GTL plant in Bintulu, Malaysia; however, research

FIG. 1. View of the Pearl GTL plant. Photo courtesy of Shell.

on this processing technology took decades to complete. Shell started conducting research on FT processes in 1973 at its labs in Amsterdam, Netherlands. The company first focused on coal-to-liquids conversion but later switched to natural gas as the primary feedstock.[245] Within these tests, the company was able to create new catalysts to produce a few grams/d of hydrocarbon liquids from natural gas. By 1983, production increased to a few bpd at Shell's pilot plant facility in Amsterdam.[246]

Less than a decade later, Shell opened the Bintulu GTL facility. The $850-MM, 12,500-bpd plant utilized Shell's Middle Distillate Synthesis (MDS) process. According to literature,[247] the MDS process is comprised of three basic stages. These stages include:

- **Stage 1:** The production of syngas from the partial oxidation process of natural gas with pure oxygen via Shell's Gasification Process.
- **Stage 2:** The syngas passes through paraffin synthesis reactors equipped with proprietary Shell catalyst. These catalyst and reactors favor the formation of long-chained liquid molecules (wax), simultaneously minimizing the formation of gaseous compounds.
- **Stage 3:** The intermediate and waxy synthetic crude oil molecules are converted and fractionated into high-quality products. The waxes are purified via a hydrogenation unit followed by advanced fractionation. Clean middle distillates and waxy raffinate are produced by a selective hydrocracking process (i.e., heavy paraffin conversion), followed by distillation.

The Bintulu GTL plant was later expanded to 14,700 bpd in the mid-2000s. Several years later, Shell and Qatar Petroleum commissioned the largest commercial GTL plant in the world, the $18-B, 140,000-bpd Pearl GTL complex in Ras Laffan Industrial City, Qatar (**FIG. 1**).

The fieldbus wars lead to a new standard in process automation. In the mid-1970s, the introduction of the distributed control system (DCS) by Honeywell and Yokogawa revolutionized process automation in the refining and petrochemical industries (the history of the DCS is detailed in the 1970s history section). This advancement in automation led to several new technologies to optimize plant operations, including the creation of fieldbus.

According to literature, fieldbus is the technology that provides a digital link between intelligent, microprocessor-based field instrumentation and the host DCS.[248] Prior to fieldbus, field instruments had to be wired in a point-to-point configuration; fieldbus enabled these instruments to communicate with the DCS using a single wire.

The origins of fieldbus technology date to the mid-1970s with the creation of the general-purpose interface bus, a precursor to Intel Corp.'s Bitbus in the early 1980s. Throughout the 1980s, several companies developed fieldbus technologies for use in several different industrial applications, including process automation for the refining and petrochemical sectors. The proliferation of fieldbus technologies in the late 1980s–mid-1990s led to many different systems that were not compatible with competing technologies, and several international standards organizations fought for their fieldbus standard to be accepted by industry. This predicament—known as the fieldbus wars—led to many users trying to seek a unified standard that enabled them to utilize different/competing technologies (i.e., a plug-and-play solution).[248] The fieldbus wars included competing standards in Europe (e.g., the French FIP vs. the German PROFIBUS, which the two later tried to combine) in the late 1980s/early 1990s and within the U.S. in the mid-1990s.[249]

In 1999, the leading fieldbus manufacturers at the time—ControlNet, Fieldbus Foundation [developed by the International Society of Automation (ISA) and purchased by the FieldComm Group in 2015], Fisher Rosemount (now part of Emerson), the PROFIBUS user organization, Rockwell Automation and Siemens—signed an agreement that put an end to the fieldbus wars.[249] This agreement became the basis for the International Electrotechnical Commission's (IEC's) IEC 61158 standard. According to literature, the IEC 61158 standard grouped the different fieldbuses into types, but created common physical, data link and application layers.[248] The standard enabled competing technologies to work with each other. Fieldbus is still in use today; however, it is being challenged by industrial Ethernet, a technology that has gained prominence since the 2010s. HP

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Excerpts from the 1990s: Process optimization, fuel quality and environmental compliance

EnCs in year 2000 and beyond

R. L. Tucker, January 1990

The future is best described in three phases: Drivers for change, current responses and projections. This article details the drivers for change within the next decade (e.g., changing workforce, competition, shrinking world, emphasis on quality, nature of projects, changing client approaches and technology availability), how the hydrocarbon processing industry's engineering and construction companies are responding to these changes, and projections for the future.

Implementing advanced controls with new DCSs

C. R. Aronson and D. C. White, June 1990

In the past few years, a new generation of distributed control systems (DCSs) has appeared. The incentives for utilizing these systems are the increases in computational capabilities, the facility for providing single operator windows and the increased potential for plant process information network development. These article will address the following three questions regarding implementation of advanced control projects:

1. What is the proper distribution of control and calculation functions between the DCS and a process computer?
2. How should the operator interface for the advanced controls be implemented?
3. What are the important factors to consider for project implementation and long-term maintenance of such systems?

EC seeks gasoline emissions control

September 1990

Gasoline emissions control is being given priority within the European Community as part of an overall strategy to reduce pollution by photochemical ozone in the lower atmosphere.

Estimating hydrogen of FCC coke

R. Sadeghbeigi, February 1991

Historically, the hydrogen content of coke has been used to judge the performance of fluid catalytic cracker (FCC) reactor strippers. The hydrogen content in coke is determined by performing an oxygen balance around the regenerator. The purpose of this article is to:

- Discuss the significance of hydrogen in coke
- Illustrate steps to calculate the hydrogen content of total coke
- Provide a graphical solution for the determination of hydrogen in coke.

Analyzing process energy efficiency

J. H. Siegell, March 1991

There are numerous methods for evaluating process energy efficiency. They involve representations of the process system to varying degrees of complexity in the search for lost Btus. A method exists which can be used to easily establish energy targets and compare current operation to these targets. This article details a new method that establishes energy targets for comparison with current operation and identifies specific areas for improvement.

Developing countries face big energy needs

HPImpact, April 1991

Developing countries must have energy to raise productivity and improve their living standards, but supplying that energy raises serious financial, institutional and environmental problems, according to a report by the Office of Technology Assessment. The report states that the magnitude of these problems underlines the need for more efficient production, transformation, delivery and use of energy.

Maximize steam generation with gas turbine HRSGs

V. Ganapathy, October 1991

Combined with heat recovery steam generators (HRSGs), gas turbines can operate in combined-cycle or cogeneration modes, thereby improving the efficiency of the overall system compared to the operation of the gas turbine alone. The type of HRSG suitable for a given firing temperature, the amount of oxygen consumed or depleted for a given fuel input, and the efficiency of the HRSG system as a function of fuel consumed are discussed.

Improve corrosion control by computer simulation

P. R. Petersen, January 1992

In many processes in refineries and chemical plants, corrosion occurs in the areas where acidic gases and water vapor condense together to form dilute solutions of acids. Results of an extensive study into the chemistry and properties of the various common neutralizing amines used to combat acid corrosion, the acids that are neutralized and the salts that are formed are reported in the work. The first section will describe theoretical considerations, lab studies and the models that were developed from these studies. The second section will discuss some of the practical applications of this knowledge.

Develop a strategic automation plan

J. B. Stout, May 1992

The development of a strategic vision, and the resulting masterplan, are the key to a successful automation program. The masterplan serves as a compass, maintaining focus on the automation journey while enabling the company to respond tactically to emerging business issues. This article examines organizations, architectures, applications and benchmarking as components of a masterplan, which is key to a successful automation program.

Trends in hydrogen plant design

T. Johansen, K. S. Raghuraman and L. A. Hackett, August 1992

Steam reforming will continue to be the main source for hydrogen production. Understanding important design considerations for hydrogen production via steam reforming require detailed attention to the many elements that comprise the process. Design trends focus on improvements to the plant's three principal unit operations:

- Generation of hydrogen/carbon monoxide syngas
- Conversion of carbon monoxide in the syngas
- Separation/purification of hydrogen from syngas.

Improve activated carbon bed adsorber operations

G. C. Shah, November 1992

Activated carbon beds (ACBs) provide the final cleanup phase of most vapor streams before venting to air. Generally, ACB applications include volatile organic chemicals (VOCs) control, odor removal and recovery/recycle of hydrocarbons.

Properly designed ACBs have a long service life; however, they do develop problems. This work provides a few troubleshooting tips to solve ACB poor performance situations.

Safety system performance terms: Clearing up the confusion

P. Gruhn, February 1993

The problem of ambiguous terms is particularly acute when dealing with safety systems. These systems are often referred to as emergency shutdown systems or interlock systems. For example, ask a chemical engineer and a safety engineer the meaning of "failure," "availability," "reliability," or "integrity" and you will probably get surprisingly different answers.

The problem is real and is causing considerable confusion in the safety control industry. This work will discuss how the industry can improve reliability and performance by using the right terminology.

Process optimization in the HPI

O. Pelham, July 1993

The increasing complexity of refineries and petrochemical plants requires closer integration and cooperation between traditional licensing activities and newer process control and optimization technologies. Greater complexity is being driven by new business, environmental and safety pressures. Advanced process control and information systems must accommodate expected changes in process configurations.

Single-sited catalysis leads next polyolefin generation

A. A. Montagna and J. C. Floyd, March 1994

New catalyst families are broadening product opportunities for polyolefins. An updated catalyst system, metallocene, has entered the technology race. This catalyst offers single-site activity, which narrows molecular weight and gives molecular weight distribution control for ethylene and propylene-based polymers. A comparative history details how metallocene-based polymers stack up to conventional Zieglar-Natta catalyst-produced resins.

New strategies maximize paraxylene production

J. J. Jeanneret, C. D. Low and V. Zukauskas, June 1994

Strong consumption growth and the shutdown of some capacity in 1992 have eliminated the surplus of paraxylene (PX) capacity, which existed from 1990–1993. PX supplies are becoming tight and market prices have risen dramatically over the last several months, sparking considerable interest in new PX production capacity. However, adding new PX capacity does not mean building new grassroots units. Additional capacity can be "found" by creative use of existing benzene, toluene and xylenes resources. By making the most of existing facilities, producers can capitalize on the current upswing of the PX market cycle.

Build pollution prevention into system design

P. P. Radecki, D. W. Hertz and C. Vinton, August 1994

Imagine using a computer-based tool that allows process designers to find and include pollution-prevention information and technology during the conceptual design stage. Emerging computer-based tools are now incorporating environmental considerations into process development.

Simplify process hazard reviews with 3D models

G. Tolpa, October 1994

Replacing plastic models with 3D electronic versions of the facility helps hazard and operability review (HAZOP) teams to increase review efficiency, reduce meeting time and record/document critical changes made during procedural meetings.

Recycle plastics into feedstocks

H. Kastner and W. Kaminsky, May 1995

Thermal cracking of mixed-plastics wastes with a fluidized-bed reactor can be a viable and cost-effective means to meet mandatory recycling laws.

Use reliability-centered maintenance to identify real-world risks

R. B. Jones, October 1995

Using reliability-centered maintenance (RCM) methods, HPI companies can make realistic, tangible progress toward reducing risk, improving productivity, minimizing downtime and increasing profitability. Because the HPI uses complex processes and operational practices to manufacture products, an effective analytical technique such as RCM is needed to help identify and mitigate high-risk situations that may occur.

Use alloys to improve ethylene production

S. B. Parks and C. M. Schillmoller, March 1996

Selecting suitable cast heat-resisting alloys for ethylene furnace tubing can cost-effectively improve product yield and selectivity, reduce downtime and lengthen production runs. Using better alloys for tubing has enabled raising temperatures,

shortening residence time and lowering pressure drop in the cracking coils. The results are increased ethylene product selectivity and yields.

EnCs adopt matrix management

J. G. Munisteri, June 1996

After a decade of restructuring and reengineering, engineering and construction (EnC) companies have discovered that the traditional corporate management system is no longer viable. Many EnC companies have adopted a matrix management as the management system of choice in effectively controlling decentralized operations. This article explores what a matrix management system is, why it is used and what it can accomplish.

Control contaminants in olefin feedstocks and products

J. A. Reid and D. R. McPhaul, July 1996

To be competitive, olefin manufacturers must use low-cost feedstocks, which frequently contain contaminants. Equally important, olefin customers, who are using newer technologies, are specifying more stringent limits on contaminants when purchasing products. These contaminants affect products and catalyst systems, hinder operating processes and impair equipment for both the manufacturers and customers.

An overview of current process designs and technologies shows several cost-effective options to reduce or remove feedstock contaminants such as carbon monoxide, carbonyl sulfide, carbon dioxide, hydrogen fluoride, ammonia methanol and phosphine.

Estimate product quality with ANNs

A. Brambilla and F. Trivella, September 1996

Artificial neural networks (ANNs) have been applied to predict catalytic reformer octane number and gasoline splitter product qualities. Results show that ANNs are a valuable tool to derive fast and accurate product quality measurements and offer a low-cost alternative to online analyzers or rigorous mathematical models.

Six critical management issues

D. M. Woodruff, December 1996

From September 1995–September 1996, a survey of critical management and workplace issues was conducted. Executives and managers were asked to list the top three issues facing their organization. The top six critical workplace issues included:

1. People issues
2. Cost and competition
3. Government regulations
4. Leadership and management
5. Change and technology
6. Quality and productivity.

Detect corrosion under insulation

M. Twomey, January 1997

Real-time x-ray technology is available to detect corrosion quickly and reliably under the insulation of piping systems without disturbing the insulation. This technology has permitted many refineries and petrochemical facilities to successfully detect this problem in an expeditious and cost-effective manner.

Economically recover olefins from FCC offgases

D. Netzer, April 1997

The concept of ethylene and propylene recovery from FCC offgases is not new; however, its application has been infrequent. Here, two approaches to olefins recovery are addressed. In the first, ethylene is recovered as a dilute gas at a concentration of about 15 vol% and serves as raw material for ethylbenzene and, subsequently, styrene. In the second approach, ethylene is recovered as a pure polymer-grade liquid. Propylene recovery is identical for both approaches.

Using mass meters for liquid measurement

K. J. Haveman and M. C. McGhee, July 1997

Mass-base flow measurement is rapidly being accepted by users in a wide variety of industries. The ability of Coriolis mass meters to handle an extensive range of applications and fluids is one reason for the swift growth in this technology. This article provides the basic theory of Coriolis meters, why mass flowmeters are selected, the most successful applications, existing and potential uses in the petroleum industry, and proper meter installation.

What are Western Europe's petrochemical feedstock options?

S. Zehnder, February 1998

In Western Europe, petrochemical demand remains strong, in contrast to stagnant oil requirements. Under these conditions, refiners have new opportunities not only as a manufacturer but also as a petrochemical feedstock supplier. Tighter gasoline specifications are rejecting olefins and aromatics from local gasoline pools. Therefore, refiners can recover propylene and xylenes from processing streams for sale or feedstock purposes. These two petrochemicals have very strong consumption demands.

How much safety is enough?

R. P. Stickles and G. A. Melhem, October 1998

Current design codes and standards primarily seek to mitigate catastrophic consequences from process incidents—standards guide engineers on how to design equipment to avoid failures. Since the focus is on consequences, these design specifications may not fully address incident frequency and provide coverage for double or triple jeopardy. Consequently, companies that seek sound guidance to correctly assess cost and benefit from loss control measures must broaden the approach and consider risk-based evaluation techniques.

Outlook for global HPI surprisingly strong

HPImpact, November 1998

Despite the maturing of the petrochemical industry, world and regional outlooks for petrochemicals are strong. High five-year petrochemical growth rates are possible if the Asian financial crisis does not continue to worsen and push the beginning of the economic recovery well beyond 2000. The global industry is forecast to grow as much as 5%/yr to 2007.

Reduce maintenance costs with smart field devices

J. S. Masterson, January 1999

Intelligent microprocessor-based field devices rapidly replacing older types of instrumentation in refineries and petrochemical plants generate vast amounts of information that can be useful far beyond the control room. New smart field devices provide processing plants with a rich opportunity to improve processes and reduce costs.

To bid or not to bid

B. Lenehan, May 1999

Bidding for large international projects can be a huge gamble, with big stake money and no game rules. Presented here is a simple method of collating and comparing requests for proposals data in a ranking order for the tender selection committee (TSC) to respond to. The bid/no bid responsibilities lie firmly with the decision-makers in the TSC; however, by using uniform data, it can quickly make balanced and consistent decisions. Over time, the data collated can also be used for analyzing the accuracy of the decisions.

Refinery air quality enforcement issues

S. P. Hampton and D. D. Bradley, August 1999

Throughout the latter half of the 1990s, petroleum refineries have experienced an unprecedented level of enforcement actions relating to environmental compliance. Air quality issues are at the forefront of most refinery enforcement activity. By understanding the regulatory requirements and managing compliance, refineries can assess potential exposure before the next scheduled environmental inspection. By reviewing these issues, refineries can prepare for agency inquiries and address potential exposure areas.

Consider using hydrogen plants to cogenerate power needs

J. Terrible, G. Shahani, C. Gagliardi, W. Baade, R. Bredehoft and M. Ralston, December 1999

Many forces are reshaping the global hydrogen market; refiners have several options to receive steam and electrical power from a hydrogen plant. The supply of hydrogen, steam and electrical power by third-party specialists can be particularly valuable when these requirements are large enough to justify the development of an independent supply infrastructure to serve multiple customers. In several case histories, the varying scenarios that simultaneously produce hydrogen, steam and electrical power from a single production plant are discussed. The integration of a steam methane reformer with various power generation technologies such as a topping turbine gas turbine and condensing turbine are explored. HP

LEE NICHOLS, VP, Content/Editor-in-Chief

The 2000s: Net-zero, environmental regulations, capacity acceleration and digital transformation

Over the past 170 yr, refining and petrochemical production has evolved immensely, not only in the sheer size of plants but also in the technologies that enable them to operate efficiently and safely. Since 2000, new regulations and technological discoveries have advanced the industry even further, leading to hundreds of billions of dollars being invested in new production capacity, as well as on new digital technologies to enhance production, safety/training, operations and supply/value chains. This final installment of the History of the HPI series details major events in the refining and petrochemicals industry over the past 20 yr, including stricter regulations/initiatives to curb carbon emissions, a safer and more environmentally friendly way to produce and handle chemicals, significant capital investments to boost production capacity and digital transformation.

Environmental issues accelerate clean fuels production and chemical operations. Since the 1970s, a prevailing trend within the HPI has been the constant pursuit of reducing sulfur content in transportation fuels to produce a higher-quality product. In turn, new technologies and regulations have led to a reduction in emissions in many parts of the world. This trend would continue for the next 50 yr as governments sought to reduce carbon emissions from industry.

Over the past 30 yr, stricter emissions standards have been enacted in many nations around the world. These standards arose from the U.S. tiered standards (e.g., Tier 1–3) and European standards (e.g., Euro 1–6, Euro I–VI) of the early 1990s and 2000s. These standards originated from research conducted on limiting smog in major cities in the U.S. and Western Europe, primarily in France and Germany. The implementation of European emissions standards in the early 1990s and 2000s would eventually become a global standard for many countries to adhere to new clean fuels regulations. For example, many nations would adopt European fuel specifications for domestically produced fuels (e.g., Bharat Stage-6 in India, China 6 in China).

The adoption of higher-quality fuel specifications does not come without a price. Hundreds of billions of dollars have been spent over the past several decades to build new secondary unit capacity additions to both remove sulfur from crude oil and boost octane levels of fuels. This trend continues today as many nations strive to produce low-sulfur and ultra-low-sulfur (ULS) transportation fuels. Many countries have invested in new units to produce higher-quality fuels, as well as increased mandatory bio-content blending rates (i.e., biofuels) and the production of renewable fuels.

Chemical regulations: Responsible Care and REACH are adopted. Strict regulations transformed the chemicals industry, as well. In the 2000s, new initiatives and regulations on the production and usage of chemicals, along with their impact on human health and the environment, became paramount, particularly in Europe but also in other producing countries.

For example, the Responsible Care initiative was established to improve the performance and environmental awareness of the global chemical industry. The initiative was launched by the Chemistry Industry Association of Canada in 1985.[250] The program evolved over the next two decades, culminating in the launch of the Responsible Care Global Charter at the United Nations-led International Conference on Chemicals Management in Dubai in 2006.[251] The charter is a voluntary commitment to safe chemicals management, performance and handling to protect both the public and the environment. According to the International Council of Chemical Associations,[250] the global charter consists of the following six elements:

1. A corporate leadership culture that proactively supports safe chemicals management through the global Responsible Care initiative
2. Safeguarding people and the environment by continuously improving the environmental, health and safety performance and security of chemical facilities, processes and technologies
3. Strengthening chemicals management systems by participating in the development and implementation of lifecycle-oriented, science- and risk-based chemical safety legislation and best practices
4. Influencing business partners to promote the safe management of chemicals within plant operations
5. Engaging stakeholders, understanding and responding to their concerns and expectations for safer operations and products and communicating openly on performance and production
6. Contributing to sustainability through improved performance, expanded economic opportunities and the development of innovative technologies and other solutions to societal challenges.

Today, Responsible Care is practiced in nearly 70 countries, representing nearly 90% of global chemical production.[251]

Approximately 1 yr after the launch of the Responsible Care Global Charter, the European Union (EU) adopted one of the most comprehensive and strictest

FIG. 1. The Paris Agreement was adopted at the UN Climate Change Conference (referred to as COP21) in Paris, France in 2015. From left to right: Christiana Figueres, Former Executive Director of UNFCCC; Ban Ki-moon, Former Secretary-General; Laurent Fabius, Former Foreign Minister of France and President of the UN Climate Change Conference; François Hollande, Former President of France. Photo courtesy of the United Nations.

laws within the chemical industry: EC 1907/2006. The EU regulation—known as the registration, evaluation, authorization and restriction of chemicals (REACH)—was put in place to protect human health and the environment from the risks posed by chemicals, as well as promote alternative methods for the hazard assessment of substances to reduce the number of tests on animals.[252] The regulation also created the European Chemicals Agency (ECHA), which manages the technical and administrative aspects of REACH.

Companies that manufacture chemicals in the EU or import chemicals into the region of at least 1 tpy must register the chemical(s) with the ECHA.[253] According to the agency, REACH applies to all chemical substances, whether they are used in industrial processes or in the daily lives of European citizens (e.g., cleaning supplies). Companies must identify and manage the risks linked to their chemicals manufactured or used within the EU. If risks cannot be managed, authorities can restrict the use of substances within the region.[252]

At the time of this publication, the ECHA has collected more than 23,000 valid REACH registrations from nearly 16,100 companies.[254]

The Paris Agreement, ensuing environmental regulations and the movement to net-zero. Over the past 30 yr, many nations have enacted new regulations and initiatives to limit carbon emissions. One of the first major global initiatives to limit greenhouse gas (GHG) emissions was the Kyoto Protocol established by the UN Framework Convention on Climate Change. Adopted in late 1997, the treaty's primary goal was to limit GHG emissions—carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, sulfur hexafluoride and nitrogen trifluoride—in 37 industrialized countries, economies in transition and the EU.[255, 256]

The protocol comprised two commitment periods. The first commitment period (2008–2012) called for participating countries to reduce emissions by 5% vs. 1990 levels. The Doha Amendment to the Kyoto Protocol in 2012 ushered in the second commitment period (2013–2020)—the amendment was signed at the 18th Conference of the Parties (COP18) in Doha, Qatar. Within this period, the participating countries committed to reduce GHG emissions by at least 18% vs. 1990 levels.[255]

The Kyoto Protocol was a precursor to the Paris Agreement. Adopted in 2015—and entered into force in late 2016—at the UN Climate Change Conference (referred to as COP21) in Paris, France, the Paris Agreement called for nations around the world to curb emissions to limit global warming to 1.5°C vs. pre-industrial levels (**FIG. 1**).[257] This agreement would usher in a new era of environmental awareness in energy production as countries and industry strived for net-zero economies and operations. At the time of this publication, more than 190 parties have signed the treaty to join the Paris Agreement.[257]

To adhere to provisions within the Paris Agreement, several countries are dramatically transforming domestic energy generation capabilities and looking to zero-carbon pathways to power their economies. The EU has been a champion for reduced emissions. Prior to the Paris Agreement, the EU had already enacted the Renewable Energy Directive (RED) in 2009, which required that 20% of the energy consumed in the EU be renewable.[258] Following the Paris Agreement, the EU revised the RED initiative by increasing required renewables usage in the bloc to 32% by 2030—this initiative was called RED 2. The European Commission (EC) proposed a revision to RED 2 in July 2021 that called for increasing renewable requirements to 40% by 2030. Within the EC's REPowerEU plan published in May 2022, renewable requirements could reach as high as 45% by 2030—the REPowerEU initiative calls for the EU to completely wean off the use of Russian natural gas supplies, a direct effect of Russia's invasion of Ukraine in 2022.[259]

The increased usage of renewables stems from the EU's Green New Deal. Approved in 2020, the ambitious initiative's goal is to make Europe the first climate-neutral continent by 2050. The policies put forth in the Green New Deal call for the reduction of net GHG emissions by at least 55% by 2030 vs. 1990 levels—the initiative is expected to cost more than €1 T.[260,261] Several of the policies put forth in the Green New Deal include decarbonizing the mobility sector (e.g., starting in 2035, only zero carbon dioxide-emitting new cars can be sold in the EU);[262] building a hydrogen economy for net-zero power generation; using alternative fuels to power shipping, rail and mass transit; and incorporating a significant amount of renewables capacity in the region.

The Paris Agreement has also inspired many other nations to invest in reducing carbon emissions within their economies. These initiatives include the use of renewable fuels; an increase in the production/blending rates of biofuels; utilizing low-carbon-emitting fuels in the marine sector (e.g., the International Maritime Organization's Global Sulfur Cap regulation was enacted in January 2020, which required marine vessels to reduce sulfur content of their fuels from 3.5% to 0.5%—the regulation affected more than 50,000 ships worldwide); an increased adoption of electric and hybrid-electric vehicles; a shift to a hydrogen-economy; and capital-intensive investments in carbon capture and storage and carbon capture, storage and utilization projects; among others.

Capacity acceleration: Rise of the East, Middle East diversification and U.S. shale. Over the past 30 yr, HPI capacity additions have significantly increased in Asia, the Middle East and the

U.S. This surge in processing capacity has equated to significant investments in new refining and petrochemical plants, expansions, grassroots facilities and gas processing/LNG infrastructure.

Asian demand leads to a surge in capital investments. In the past 20 yr, more than 1 B people in Asia have moved into higher socioeconomic classes. For example, in 2000, less than 1 B people in Asia were considered part of the consumer class (i.e., those that spend more than $11/d). By 2020, that number increased to 2 B, and forecasts show that Asia's middle class could reach more than 3 B by 2030.[263,264]

Since 2000, several Asian nations have witnessed a surge in industrial activity, leading to a steady growth in domestic economies. As many Asian nations' economies grew, surging demand for refined fuels, petrochemical products and natural gas led to a flood of capital investments in new processing capacities. From 2000–2021, oil consumption in Asia skyrocketed more than 12.6 MMbpd to nearly 34 MMbpd, according to bp's *Statistical Review of World Energy*.[181] In response, the region has added nearly 15 MMbpd of refining capacity (net). China alone has added more than 10.7 MMbpd within the same timeframe.[181]

Much of these capacity additions adhere to European fuel specifications (e.g., Euro 3, 4 and 5)—clean fuels (ULS gasoline and diesel) regulations have become a global initiative to limit smog/pollution, especially in major cities. To produce ULS fuels, Asian producers have built some of the most complex refining networks in the world.

Along with increased demand for transportation fuels, Asia's thirst for petrochemicals and natural gas have expanded exponentially—the region's natural gas consumption has nearly tripled to more than 860 Bm^3y since 2000.[181] Consumption of petrochemicals in Asia has increased by tens of millions of tons per year as more individuals move up socioeconomic classes and demand more products comprised of thermoplastics. In turn, Asia has invested hundreds of billions of dollars in new petrochemical capacity additions over the past 20 yr. These investments include grassroots facilities, expansions, upgrades, mega-integrated complexes and the installation of new petrochemical plants into existing refining operations.

To help decarbonize economies, many Asian nations have invested in new natural gas infrastructure over the past decade. For example, several Asian countries have converted coal-fired power plants to use natural gas. However, many Asian nations must import natural gas supplies to use as feedstock for power generation. In turn, the region has built tens of millions of tons per year in new LNG import infrastructure and tens of thousands of miles of natural gas pipelines. Capital-intensive natural gas/LNG infrastructure buildouts continue today.

The Middle East diversifies its products portfolio. The Middle East has changed drastically since oil was first discovered in Persia (modern-day Iran) in 1908. Approximately 4 yr later (1912), the region's first refinery was built by the Anglo-Persian Oil Co. (APOC) in Abadan—APOC would later adopt the name bp after the British became the majority

Improve Operations by Considering Total Cost of Ownership for Isolation Valves

When planning new projects and evaluating unit maintenance costs, it is best practice to consider equipment as an investment and calculate the total cost of ownership to select the best equipment. Calculating the total cost of ownership considers equipment acquisition, maintenance, repair, and replacement costs during a specified time. Calculating the total cost of valve ownership, specifically for isolation valves, can help eliminate unscheduled shutdowns due to valve failures that can risk safety or damage equipment.

DEFINING RISKS

Define isolation valve "failures" and their risks. Each unit may have different recurrent issues that can cause big problems. Some of those may be leaks through the stem that create fugitive emissions, internal leaks through the seats (of a closed valve) that degrade efficiency, or valve stroke issues that can have catastrophic consequences.

COSTS TO CONSIDER

To evaluate the total cost of ownership, define time range, identify the valves to analyze, and calculate total maintenance costs.

1. Define the time range

To comprehensively analyze the economics of a valve purchase, we recommend using two operating windows or maintenance cycles (scheduled plant shutdowns).

2. Identify the valves to analyze

We recommend analyzing no more than four valves for simplicity. Choose valves that have some relationship to each other. This enables understanding their operational effect on the plant.

3. Calculate total maintenance costs (purchase, install, maintain, repair, replace)

Include the valves' initial purchase price, installation cost, preventive maintenance costs, repair costs (multiplied by the number of repairs expected during the valves' operational life), and replacement costs (multiplied by the number of replacements expected during the identified period).

To fully evaluate a valve purchase, consider the costs of valve failures, such as unscheduled shutdown and efficiency-related costs.

A valve failure can cause an unscheduled shutdown if it creates a safety risk to people or the environment or damages equipment. Determine whether the process must be stopped completely to replace the valve, reducing production or if it is a batch process that requires an extended cycle time due to the intervention. To quantify the costs, start with the per-day cost of a unit shutdown; divide it into an hourly cost; then multiply by the number of hours needed to repair or replace the valve.

Efficiency-related cost analysis is one of the most complex because it requires high-level process knowledge. Consider increased fuel consumption, lengthened operating cycles for batch applications, and increased downtime due to leaking valves.

If an isolation valve of a multi-train coking system leaks, the pressure available for the cutting water system declines, increasing the time required to decoke the reactors. This longer coking/decoking cycle shrinks overall production.

In refinery fractionator-tower bottoms systems with two pumps, one pump must be periodically shut down at a time for maintenance. In this case, the failure of an isolation valve will considerably escalate downtime.

EXAMPLE ANALYSIS

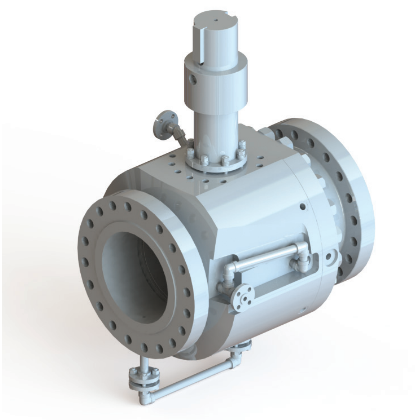
The total cost of ownership for a catalyst withdrawal application in an FCC unit using the time range of 10 years or two operational windows.

Solution 1

- Two gate valves
- Operational window: five years
- Shutdown cost: $250K US per day
- Replace Valve 1 annually
- Replace Valve 2 every two to three years
- Time required to change Valve 1: one hour
- Time required to change Valve 2: 36 hours
- Valves 1 and 2 begin to leak after six months of operation
- Catalyst loss per day: 2lb/day average during six months

Solution 2

- Two ValvTechnologies' zero leakage ball valves for isolation and a gate valve for throttling



ValvTechnologies' custom purge configuration removes and displaces hot bitumen, eliminating coke fouling and increasing the mean time between repairs reducing the total cost of ownership.

- Operational window: five years.
- Shutdown cost: $250K US per day
- Replace Gate Valve every two years
- Replace ValvTechnologies' Valve 1 every five years
- Replace ValvTechnologies' Valve 2 every 10 years
- Time required to change Gate Valve: one hour
- Time required to change Valves 1 and 2: zero because it is performed at the scheduled shutdowns
- No catalyst loss

The total cost of ownership for Solution 2 is just 25% of Solution 1, despite its higher initial investment. The difference is over the ten years, costs for unscheduled shutdowns and catalyst losses have been eliminated, saving both cost and headache.

Similar analysis has shown comparable results in a variety of processes. Contact ValvTechnologies to discuss your project and custom solutions.

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FIG. 2. Construction on the 615,000-bpd Al Zour refinery in Kuwait. The refinery was commissioned in 2Q 2022. Photo courtesy of Kuwait Integrated Petroleum Industries Co.

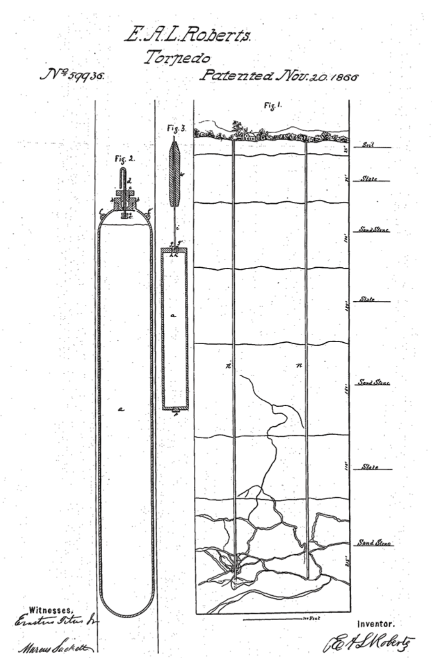

FIG. 3. View of Roberts' exploding torpedo. Photo courtesy of the U.S. Patent Office.[272]

shareholder in the company.[8] More than 100 yr later, the Middle East has not only become a major oil producing and exporting region but has also invested heavily in the production of transportation fuels, petrochemical products and natural gas.

Major regional investments in hydrocarbon processing plants accelerated in the 2010s, primarily due to dramatic volatility in crude oil pricing. In 2012, global crude oil prices skyrocketed to more than $120/bbl due to an improving global economy, increased oil demand, oil speculation and Iranian sanctions.[265] Western nations sanctioned Iran due to the country's pursuit of a nuclear program. These sanctions had the potential to knock more than 2 MMbpd of Iranian oil exports off the market and lead Iran to retaliate by closing the Strait of Hormuz, a narrow waterway between the Persian Gulf and the Gulf of Oman—approximately one-third of waterborne oil shipments pass through the strait daily.[266]

However, the forecasted oil consumption never materialized, and prices took a freefall. From 2014–2016, global oil prices fell from $120/bbl to less than $30/bbl. The significant decline in oil prices severely dented Middle Eastern oil revenues, the primary source for the region's economies.

Although several capital-intensive projects had been announced in the region prior to the crude oil price plunge (e.g., aromatics and methanol plants in Oman; Borouge 2 construction in the UAE; and major projects by NATPET, PetroRabigh, SATORP and SADARA in Saudi Arabia), nearly all Middle Eastern countries announced major capital investments in new hydrocarbon processing capacity to both mitigate the reliance on oil export revenues and diversify their product portfolios.[267] These investments focused on grassroots refining and petrochemical facilities, clean fuels production, integrated complexes and natural gas infrastructure (e.g., gas processing plants, LNG terminals, pipelines).

For example, the following are major investment commitments—many capital programs continue into the mid- and late-2020s—from various Middle Eastern nations since the mid-2010s:

- Kuwait invested more than $30 B on the Clean Fuels Project and 615,000-bpd Al-Zour refinery (FIG. 2) to become the region's leader in clean fuels production
- Oman invested and continues to invest more than $15 B to boost processing infrastructure
- Saudi Arabia has and continues to invest tens of billions of dollars in refining and petrochemical capacity additions as part of the country's Vision 2030 initiative
- Qatar is investing $30 B to increase domestic LNG liquefaction capacity from 77 MMtpy to more than 125 MMtpy by 2027
- The UAE continues to invest billions of dollars to expand domestic refining capacity and triple petrochemical production capacity as part of Abu Dhabi National Oil Co.'s (ADNOC's) 2030 Strategy
- Bahrain continues to invest billions to expand and modernize its refining industry
- Iran, despite years of sanctions, has and continues to invest heavily in increasing domestic refining and petrochemicals capacities.

These investments have not only created millions of jobs within the region but have also provided Middle Eastern nations with new high-quality products for export to the global market, providing tens of billions of dollars in trade revenues.

U.S. shale transforms the U.S. processing landscape. One of the most impactful events in the history of the U.S. hydrocarbon processing landscape was the discovery of hydraulic fracturing (fracking). Although the technology came into prominence in the 2000s, the history of fracking dates to the 1860s. During the Battle of Fredericksburg, Virginia in the U.S. Civil War, Colonel Edward A. L. Roberts noticed how exploding Confederate artillery rounds affected a narrow canal on the battlefield. This observation was the genesis of the technique Roberts called superincumbent fluid tamping.[268] According to literature, superincumbent fluid tamping is when water dampens an explosion, preventing any debris from blowing back up the well hole, thus amplifying its effects.[269] This technique spawned Roberts' invention of the exploding torpedo, which he believed could be used in the burgeoning oil production industry.

The exploding torpedo was an explosive device that would fracture the surrounding rock at the bottom of an oil well to stimulate flow. The torpedo was an iron case filled with 15 lb–20 lb of gunpowder. It was lowered to the bottom of an oil well and detonated via a wire running from the shell to the surface. The explosion filled the borehole with water (i.e., fluid tamping), which concentrated the explosion, providing a more efficient fracture of surrounding rock.[270,271] After several successful tests, Roberts patented his exploding torpedo in 1866 (**FIG. 3**), eventually switching from gunpowder to nitroglycerin.

Modern-day hydraulic fracturing began in the 1940s with experiments conducted by Floyd Farris of Stanolind Oil and Gas Co. These experiments included injecting 1,000 gal of gelled gasoline and sand into gas-producing limestone in the Hugoton gas field in southwest Kansas (U.S.). This was followed by injecting a gel breaker to stimulate the well.[273] Although the tests were not successful in significantly increasing well production, it did mark the beginning of modern-day fracking.

In 1949, Halliburton Oil Well Cementing Co. (Halliburton today) began its own fracking experiments in Oklahoma (U.S.) and Texas (U.S.), which were much more successful. Over the next 30 yr, fracking grew in prominence in the U.S. In the 1980s and 1990s, George P. Mitchell incorporated a new technique in oil production that combined hydraulic fracking with horizontal drilling—this technique also used slick water, a combination of water, chemicals and sand that could increase the pressure in the rock formation. Mitchell's company (Mitchell Energy and Development Corp.) conducted several successful experiments in the Barnett Shale formation in Texas, which spread into other shale basins in Arkansas, Louisiana, Pennsylvania, West Virginia and states in the Rocky Mountain region, thus launching the modern-day shale revolution.[269] By 2020, fracking enabled U.S. producers to significantly expand domestic oil and natural gas production—the nation's oil production increased from approximately 7 MMbpd in the early 1990s to more than 12 MMbpd, with domestic natural gas production nearly doubling to more than 1.1 Bm^3y within the same timeframe.[274,275] The proven success of fracking propelled the U.S. to the forefront of global oil and natural gas supplies and had dramatic impacts on the region's hydrocarbon processing capacity.

Prior to the 2010s, the U.S. was a major importer of natural gas, with many investors eager to build large-scale LNG import terminals. However, that all changed post-2010. As U.S. natural gas production surged because of widescale fracking, the nation had an abundance of natural gas supplies. To monetize this commodity, public and private companies invested a significant amount of capital to build gas processing plants, natural gas pipeline infrastructure and grassroots LNG export terminals or convert existing LNG import facilities to export operations. By the early 2020s, operable U.S. LNG export capacity eclipsed 80 MMtpy, with additional liquefaction trains under development that will increase total U.S. LNG export capacity to more than 100 MMtpy by the mid-2020s. Within a decade, shale gas production had enabled the U.S. to reverse course from importing vast amounts of natural gas to being one of the largest natural gas exporters in the world.

Shale gas fracking also revitalized the country's petrochemicals sector. Cheap, readily available shale gas feedstock (e.g., ethane) enabled the country to become one of the world's lowest-cost ethylene producers—ethylene is the key building block for the petrochemical industry; it supports 70% of petrochemical industry production and is used to manufacture a wide variety of products for industrial and consumer markets. In turn, more than 11 MMtpy of ethylene production units began operations from 2016–2020, with an additional 5 MMtpy set to start production by the mid-2020s. This wave of investments in ethane cracking facilities spurred tens of billions of dollars in capital investments in ethylene derivatives and specialty chemicals production capacities, as well as ammonia, urea and methanol production plants. The increased production of chemicals and petrochemicals also had profound effects on the nation's chemical trade, increasing chemical export revenues from $227 B in 2015 to more than $243 B by 2020.[276]

Digital transformation: Advancing the HPI into Industry 4.0. The HPI's digital prowess has dramatically evolved since the first direct digital control computer was installed in a refinery—the Thompson Ramo Wooldridge 300 computer was incorporated at Texaco's 1,600-bpd polymerization unit at the Port Arthur refinery (Texas, U.S.) in 1959 (the history of this event was chronicled in the History of the HPI section of the 1950s). This event marked the beginning of the computer-integrated manufacturing era for the HPI.

The 1950s also witnessed the beginning of computer-aided design (CAD) and the advent of research into artificial intelligence (AI). CAD was coined by Massachusetts Institute of Technology professor Douglas Ross, who was known as the father of automatically programmed tools, the language that drives numerical control in manufacturing.[277] This technology would evolve and heavily influence advanced engineering and design software for hydrocarbon processing plants/complexes in the following decades, enabling plant design, engineering and construction companies to create advanced models and drawings.

The field of AI research began in 1956 with the Dartmouth Summer Research Project on Artificial Intelligence held by John McCarthy in Hanover, New Hampshire (U.S.) (**FIG. 4**).[278] The 2-mos brainstorming session included approximately 20 participants that discussed various topics such as neural networks, computers, computational theory and natural language processing, among other topics—several of these topics were influenced by theories and concepts put forth by English mathematician and computer scientist Alan Turing within his paper "Computing machinery and intelligence;"[280] his creation of the Turing machine demonstrated the concepts of algorithms and computation, which is why he is considered to be the father of theoretical computer science and AI.[281,282] Over the next 20 yr, research into AI flourished, with heavy funding being poured into the technology by entities such as the British and U.S. governments. However, research slowed in the late 1970s and funding ran dry—this period was known as the "AI winter."[282]

In the 1960s, the invention of the programmable logic controller (PLC) by Bedford Associates (the company became part of Schneider Electric in the 1990s) meant that large banks of relays could be replaced by a single device (a history of the PLC is detailed in the History of the HPI section of the 1960s). PLCs

were incorporated into plant operations in the late 1960s/early 1970s.

During the late 1960s, French engineer Pierre Bézier created the first 3D CAD/computer-aided manufacturing program while working at the French automobile maker Renault. His invention, the UNISURF CAD system, enabled the design of vehicles to move from drawing boards to CAD.[283] This technology would evolve over time and create different approaches to 3D: surface modeling and object modeling.[284] During this timeframe, computer-generated environments that responded to the user started to take shape. Myron Krueger coined this type of technology system "artificial reality."

In the 1970s, the creation of the distributed control system by Yokogawa (Japan) and Honeywell (U.S.) revolutionized refinery and petrochemical plant operations. This technology moved process controls from board operations (i.e., large instrument panels that housed controllers) to a computerized control system, enabling full automation of plant operation.

FIG. 4. Several of the scientists that attended the Dartmouth Summer Research Project on Artificial Intelligence in 1956. Photo provided by Margaret Minsky.[279]

FIG. 5. New AR/VR technologies can combine IIoT data and AI-infused analytics to enable users to interact with digital twins of their facilities. Photo courtesy of AVEVA.

Process automation continued to evolve over the next several decades, including the development of fieldbus, ethernet-based networks, virtual reality (VR), wireless systems and protocols, increased cyber defenses, remote transmission and many other advances to optimize plant operations (e.g., the invention of the internet enabled companies to take advantage of cloud computing).

The advances in computing technology, AI, VR, augmented reality (AR) and other dynamic digital technologies culminated in the age of digital transformation of the 2010s—referred to as Industry 4.0 or the Fourth Industrial Revolution. This era is revolutionizing the way companies do business by using digital technologies to build and run more efficient and smarter operations and supply/value chains. Within the processing industries, the age of digital transformation has provided refiners and petrochemical producers with new digital technologies—the Internet of Things (IoT), digital twins, cloud computing, smart sensors and networks, AI/VR/AR, predictive/advanced analytics, drones, blockchain and other devices and hardware/software (FIG. 5)—to enhance production, automation, supply chains, maintenance, training, safety and profitability.

Inspiring future pioneers. This series has detailed the major events, people and technological advancements in the global refining and petrochemical industries over the past 170 yr. From the discovery of kerosene as a lamp burning fuel in the mid-1800s to the complex processes used today to produce transportation fuels, thermoplastics, fertilizers and many other products used by billions of people daily, this robust analysis has chronicled the evolution of the global HPI.

This anthology has highlighted the origins of refining; the genesis of synthetic plastics and oils; the creation of the internal combustion engine and jet engine, thermal and catalytic cracking, different types of polyethylene and resins, new catalysts technologies (e.g., Ziegler-Natta) and rocket fuel; how war necessitated advancing technologies such as 100-octane aviation gasoline, synthetic rubber and silicones; the era of computer-integrated

manufacturing; the creation and advancement of the distributed control system, the PLC, fieldbus and ethernet; multiple oil crises; a significant increase in clean fuels, emissions reduction and safety regulations globally; liquid crystals and conducting polymers; digital transformation; and new tools, processes and technologies to optimize maintenance, plant design/engineering and construction, training, management and operations.

This series has been a testament to the ingenuity of people from around the world that have contributed to the evolution of societies through discovery and creation. These advancements have increased the standard of living for billions of people around the world for more than a century. Unless we tell their stories and discoveries, most will be lost in history. Instead, these stories and accomplishments should be celebrated in hopes of inspiring new generations of innovators, risk-takers, creators and developers to be pioneers for new technologies, processes and inventions to the betterment of humanity. HP

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Excerpts from 2000–2022: Decarbonization, digital transformation, integration and reliability

*HP*Insight: A new era for the HPI

S. Romanow, January 2000

Will the new millennium push the HPI into a new era? For many years, we have discussed how the HPI would become a global industry. It has evolved into a globalized industry. So, how did it happen? Much of the metamorphosis is directly attributed to technological breakthroughs, especially in information technologies. Developments in PCs, communication systems, information-management technologies and software removed barriers to collecting, utilizing and transfer of real-time data. The internet has had the most profound effect in a short time span. It has erased more barriers and enabled access to tremendous information sources.

Improve startup of an olefins complex

K. Bush, G. Duarte and A. Pohlmann, June 2000

What are the critical elements affecting an olefins unit startup—engineering/design techniques, license technologies, construction activities, training of operators, composing precommissioning/operating procedures, site support/involvement from equipment venders, etc.? All these listed factors—in varying degrees—will influence the design, construction, precommissioning and startup of a new plant. This article provides a successful startup of COPESUL's olefins plant in Triunfo, Rio Grande do Sul, Brazil.

Project alliance delivers "green fuels"

M. Entwistle and P. Watson, February 2001

The growing worldwide trend towards tightening of gasoline and diesel fuel specifications around the world has created an opportunity for leadership in the delivery of clean fuels. This article details bp's $500-MM Queensland Clean Fuels Project in Brisbane, Australia and how several entities worked together to build a highly integrated clean-fuels refinery ahead of schedule.

Acoustic fatigue in large turbocompressors and pressure reduction systems

L. E. Blodgett and D. E. Jungbauer, August 2001

Predicting the potential for acoustic fatigue in piping systems associated with pressure reducing systems in the design stage has received much attention. Based on theory and empirical measurements, a near-field sound pressure level screening method has been developed for evaluating piping systems. This article presents a case history that incorporates the use of the near-field noise screening criterion for risk assessment in an existing installation. This screening criterion will enable users to assess the risk and severity of acoustic fatigue, leading to safer systems and help to determine the need for additional measurements and analysis.

Improve estimations for dynamic pressure waves from an explosion

S. A. K. Suri and I. Chowdhury, October 2002

What is the best method to estimate the blast pressure force on buildings and/or structures within a plant facility? Due to the nature and quantities of flammable materials flowing in pipes and stored in tanks and reactors, engineers must estimate the consequences should an explosion occur within a complex hydrocarbon processing plant. Using a polar coordinate system, engineers can estimate risks on buildings and structures during the design phase.

Use PdM to optimize pump overhauls

R. Beebe, April 2003

Pumps are arguably the most common machine in the power and process industries, yet relatively little information is available on applying predictive maintenance (PdM)/condition monitoring. This work provides some basic condition monitoring tests for pumps, along with a case study to show how applying condition monitoring by vibration and performance analysis on a pump solved some problems.

Cybersecurity: Are your computer control systems safe from attack?

P. Baybutt, March 2004

Cybersecurity is an established discipline for commercial and business computer systems but not for manufacturing and process control computer systems in the HPI. Cybersecurity typically has focused on information or data security so it cannot be read or compromised. However, the nature of attacks has changed as technology and opportunities have evolved. If a company does not employ good cyber security, it is imperative to conduct a cybersecurity vulnerability analysis to properly protect crucial systems from attack.

Direct heat recovery of a cogeneration unit saves utilities and reduces emissions

E. Goudappel and J. Sentjens, July 2004

Refineries are faced with drivers pushing their performance to less emissions and higher utility efficiency. Direct heat re-

covery of a cogeneration unit, by means of a heat recovery unit, maximizes the integration potential, resulting in reduced emissions and utility savings, as well as reducing fouling/coking and an improved energy intensity index.

Trends in laser scanning systems to support revamp/retrofit projects

J. Sanins, December 2004

The growing trend toward retrofit/revamp projects has focused on more cost-effective, cost-efficient ways to capture as-built engineering data directly quickly and accurately from existing facilities. This highly accurate data can then be integrated with 3D computer-aided design (CAD) modeling tools to design new plant features within the existing facility as part of engineering execution.

Model-based predictive control increases batch reactor production

A. Cardete, R. Lucio, R. Martinez, S. Munoz, A. Sanz, J. Papon, C. Ruiz and D. Ruiz, May 2005

After a feasibility study, Repsol YPF decided to apply a model-based predictive controller to a batch reactor producing polyols. The predictive controller for reactors (PCR) is a set of control modules that are designed to face most of the reactor configurations. The important increase of production is a consequence of the better handling of the reactor temperature. Here's a description of the unit and control objectives, methodology, project steps, results and the corresponding benefits.

Consider modifying your refinery to handle heavy opportunity crude oils

A. Harji, M. Rodwell and R. Henderson, September 2005

The incentive to process heavy, sour crude oil has never been greater, as some regional sour-crude discounts are approaching $20/bbl. Unfortunately, the lower cost crude oils have physical properties that limit their processing at most North American refineries. What modifications are needed for a conventional refinery to capitalize on this potential cost savings? To process high-sulfur crudes, refiners must retrofit older processing units to capitalize on 'dirty' feedstocks.

Convert oil sands into distillate cost-effectively

T. Okui, T. Shigehisa, M. Tamura, M. Yasumuro and S. Yui, January 2006

Demand for energy remains robust even at high crude oil prices. Oil sands are new hydrocarbon resources that can be converted into high-quality (low-sulfur) distillates for refining and petrochemical applications. With crude oil prices above $60/bbl, oil sands bitumen is a viable resource that can be refined. New slurry phase hydrocracking and two-step hydrotreating developments have proven to be very successful in upgrading Athabasca oil sands bitumen into low-sulfur, high-cetane distillates. The produced refinery-grade naphtha and heavy gasoil can be readily used as a feed to the catalytic reformer and fluid catalytic cracking unit.

Apply a comprehensive approach to biofuels

M. Koskinen, M. Nurminen and M. Sourander, February 2006

The European Union (EU) is actively defining the total goals and requirements for automotive fuels. As part of this on-going effort, the EU has defined clear targets to increase usage of renewable materials as part of the transportation fuels market. Biomass-based renewable fuels are produced outside of refineries. However, there are profitable opportunities to incorporate bio-mass-based materials into the refining industry. Modern biofuels or components can be produced and used as part of upgrading processes for a refinery.

Improve naphtha quality for olefins cracking

V. L. Bhirud, April 2007

Over 50% of the world's ethylene capacity is naphtha based. As crude prices increase, so does the cost of naphtha for liquid crackers. Ethylene producers shun naphtha feedstocks containing high-aromatics content. Aromatics provide no net value to the cracking process. Integrating an aromatics-extraction unit with a naphtha hydrotreater can remove the problematic aromatics from heavy feedstreams. Pretreating off-grade naphtha can yield a high-quality feed for liquid olefins crackers.

In pursuit of flawless project execution

J. Caglar and M. Connolly, December 2007

Main automation contractor (MAC) and main electrical contractor (MEC) contracts are becoming the preferred strategy for users looking to satisfy the exacting technical and execution requirements for automation and electrical systems in refineries, petrochemical and gas processing facilities. This article discusses how a MAC/MEC approach that includes technology and solutions, combined with services capabilities and comprehensive project execution, benefits users in today's flat world.

Smart actuators can prevent valve failure during critical events

E. Carey, November 2008

Smart electric actuators were designed to ensure the critical-service valves can perform when called upon. Developed approximately 15 years ago, smart actuators contain intelligence that used to be included in the control room of plant operations. Today, smart actuators have as much, if not more, intelligence as the old control rooms.

Is nitrogen really inert as a blanketing medium?

K. Luckwal, K. K. Mandal and K. R. Ramakumar, August 2008

Blanketing a drum or a tank with inert gas such as nitrogen is done for various reasons. However, when there are insufficient nitrogen supplies within the refinery, the blanketing medium is changed to the fuel gas mode. During this change, the behavior of various processing conditions changes drastically and requires close monitoring. In general, it is believed that the solubility of gases decreases with increasing temperatures. But that is not always true for all gases; nitrogen behaves differently. We will explore the solubility of nitrogen from the thermodynamics point of view.

Why do I need to inventory greenhouse gas emissions?

D. V. Bubenick, G. M. Combs and A. M. Mazzoccoli, April 2008

Right or wrong, the tide of public opinion has reached such overwhelming proportions that it is now a matter of when, not if, individual petrochemical facilities around the world are going to have to develop inventories of their greenhouse gas (GHG) emissions on a continuing basis. Globally, the EU is already re-

quiring facilities within its member countries to report GHG emissions and to meet reduction targets in accordance with the Kyoto Protocol. Other countries around the world are in the process of implementing similar programs.

What is driving changes in polyolefin catalysts and catalyst technology?

J. Hain, A. Hummel, M. Jensen and A. Myers, April 2008

In 2007, polyolefin demand was two-thirds of total thermoplastic demand or more than 110 MMt. By 2012, polyolefin demand is expected to be almost 150 MMt. Polymer demand grows quickly in developing countries as they move toward a consumer-based economy. While the polyolefin industry enjoys increasing polymer demand and high operating rates, producers face many of the same challenges that threaten the profitability of other industries:

- Threats from low-cost imports sourced from feedstock-advantaged Middle East producers
- High natural gas and crude oil prices putting upward pressure on production costs
- Industry consolidation has created fewer but larger producers who control larger market shares and more assets. Traditional ownership by oil and gas companies is not the rule anymore. Financial firms are showing interest in ownership and changing the way these companies are managed.

Are floating LNG facilities viable options?

A. J. Finn, July 2009

Technology developments in offshore LNG storage and transfer have made offshore LNG production commercially viable. Due to rising costs for onshore LNG facilities, floating LNG (FLNG) is cost competitive. Techno-commercial issues associated with floating LNG and how they are resolved will be discussed.

What metals should be used in critical service heat exchangers?

R. Pramanik, August 2009

In heat exchanger applications, titanium (Ti) and its alloys are increasingly replacing copper-nickel alloys as construction materials for seawater service. However, some specific issues related to the design and fabrication of Ti-based shell-and-tube heat exchangers have surfaced. The presented strategies will focus on developing design criteria to optimize heat exchangers without compromising the quality of fabrication. The presented case history will explore issues with special emphasis on the design, material selection and fabrication of various components of shell-and-tube heat exchangers from Ti and Ti alloys.

Improve usage of regenerated refining catalysts

G. J. Yeh, February 2010

A major Middle East oil company uses regenerated hydrocracking catalysts up to three regenerations by ex-situ and regenerated semi-regen naphtha reforming catalysts up to 10 regenerations by in-situ. This article explores common practices in the refining industry regarding the application of regenerated hydrotreating, hydrocracking and semi-regen naphtha reforming catalysts. Presented guidelines over regenerated catalysts show how refiners can save by using regenerated catalysts or enhance revenue by using the fresh catalysts.

Improving pH control mitigates corrosion in crude units

D. L. N. Cypriano, J. A. C. Ponciano, A. T. Vilas Boas, P. D. Murray and M. R. Nasser, March 2011

For crude-unit overhead systems, pH is the main process parameter that impacts corrosion rates. To control corrosion conditions, many operators use various neutralizers at optimum ranges determined by site-specific conditions. A four-year study (2005–2008) was conducted at a Petrobras refinery using amine-blend solutions to control pH. Over this period, corrosion rates were measured through ultrasonic inspections and weight-loss coupons. This investigation proved that maintaining a low chloride level and stable pH levels were the most effective ways to control equipment damage from corrosion.

Overcome challenges in treating shale gases

R. H. Weiland and N. A. Hatcher, January 2012

Shale represents an astonishingly large, new source of natural gas and natural gas liquids (NGLs). However, a common misconception seems to be that, for the most part, shale gases are sweet and do not need to be treated. Shale gas tends to have considerable variations from play to play and even from well to well within the same play. This article describes several challenges in processing shale gas and how to overcome them.

Alternative feedstock options for petrochemicals: A roadmap

M. O. Garg, S. K. Ganguly and S. Sen, April 2012

Following the economic slowdown in the U.S. and Europe, a gradual demand shift has occurred from west of the Suez to east of the Suez. Asia-Pacific nations are the areas for energy and petrochemical-based product demand growth. After China, India is the next growth hub for chemicals. A steadily growing middle class is a significant driver in India's economy and supports new petrochemical/chemical consumption. This young population with rising incomes is responsible for growing demand for consumer durable goods, such as automobiles and packaging. Petrochemicals constitute over 20% of the total chemical sector output—63% as polymers and 29% as synthetic fibers. To satisfy demand, new hydrocarbons will be needed to meet future demand.

Maximize diesel production in an FCC-centered refinery

P. K. Niccum, September 2012

For refineries with an FCC unit as the main conversion vehicle, ongoing debate is how existing refinery assets can best be used to economically increase diesel production. This article presents methodologies for maximizing the production of high-quality diesel in a refinery that relies on FCC as its principal means of heavy oil conversion.

Use 3D visualization to improve refinery engineering and design

S. Bennett, June 2013

One of the most significant outcomes of rapidly increasing computing power has been in 3D visualization. Technology involving 3D visualization has long been essential to the work of the engineering designer, but lush visual rendering has historically been sacrificed for more immediately productive uses of available processing power, such as responsiveness and sophis-

ticated clash detection. However, to overlook the potential of realistic 3D representation is to miss an opportunity to increase design productivity and quality.

A biofuels roadmap for Europe to 2030

A. Bauen, February 2014

What will the transport sector use as an energy source in 2030? If you answered gas, electricity or hydrogen, you could be on the right track. These sources are becoming increasingly useful to meet clean energy requirements.

Improve execution of capital projects with advanced technologies

A. A. Avidan, December 2014

The engineering and construction (E&C) of capital projects has changed significantly over the past few decades. These changes have been driven by advanced information technologies, which have also had major impacts on all aspects of our lives. These developments involve how project information is managed and handled and include CAD, transition to building information modeling, the cloud, VR, big data, the Internet of Things and robotics, among others.

Use cloud-based document collaboration to complete projects

S. Baird, February 2015

Capital and maintenance projects require the management of thousands of documents, which can be more easily accomplished with cloud-based solutions.

How Cr compounds discolor refractory brick walls of an ethylene cracking furnace

A. Al-Meshari, M. Maity and E. Al-Zahrani, April 2015

Unusual pink coloration was noticed on the entire refractory brick wall in the radiant section of an ethylene cracking furnace of a petrochemical plant. The results of examinations and analyses showed that the deposition of chromium (Cr) species on the refractory wall appeared to originate from the radiant alloy tubes and contributed to the pink coloration of the refractory brick wall. The suspected cause was the spontaneous formation of chromium oxide on the tubes at high temperature, followed by oxidative vaporization that was likely due to the increase of the tube metal temperature to values above design.

How to cost-effectively adapt to a tight oil world

D. Lindsay, M. Griffiths, A. Sabitov, D. Sioui and B. Glover, July 2015

The increase in domestic production of light tight oil (LTO) has resulted in rapid shifts to processing these crudes in North American (NA) refineries. LTOs typically have a much higher content of light material compared to the traditional light sweet crudes that most NA refineries have processed. While these domestic crudes offer lower-cost raw materials, there are inherent limits to the amount of LTOs that can be processed by installed assets. These limits can result from the additional light content or from feed quality parameters, such as the high paraffin content that is characteristic of most LTOs. Addressing these limitations will enable capturing the higher value from LTOs.

Utilize an optimizer to blend gasoline directly to ships

W. Scriven, A. Martin and D. S. Seiver, June 2016

A new control system and single-blend optimization system make it possible to blend gasoline directly into tanker ships for delivery, rather than only into tanks, thereby saving millions in capital and reducing product giveaway.

Optimize a CDU using process simulation and statistical modeling methods

J. Bird, D. Seillier and E. Piazza, October 2016

A methodology was implemented to optimize the operation of a refinery crude distillation unit using a combination of process simulation and statistical modeling methods. The primary objective was to estimate a set of operating targets for column pumparound and bottoms stripping steam flows. These targets were established to maximize the unit profitability over a typical range of crude rate and crude quality operating conditions.

Shift to gas: A contribution on the path to sustainability

E. Koenig, January 2017

The COP21 event left the world with new mandates to develop and implement low-emissions energy sources to power the global economy. To limit global warming, the world must increase the use of resources like natural gas, which offers a quick, relatively clean and inexpensive interim step in the global transition from high-emissions resources to renewable energy sources.

HF alkylation conversion is finally within reach

J. Nunez and S. Presley, September 2017

The predominant alkylation technologies utilized by refiners require either sulfuric acid or hydrofluoric acid (HF) to catalyze the reaction. Due to the volatile and toxic nature of HF, refiners have long sought out cost-effective solutions to convert HF alkylation units to safer sulfuric acid alkylation technology. However, with the perceived high cost of conversion and a lack of a regulatory requirement to make this change, refiners have yet to convert an HF alkylation unit to a sulfuric acid alkylation unit. At present, HF conversion is finally within reach thanks to the development of cost-effective and proven technologies.

Preparing for a sea change in global refining

C. Follette and J. Ruiz-Cabrero, November 2017

Beginning in 2020, the new IMO regulations will reduce the limit of sulfur content in marine fuel from 3.5% to 0.5%. In turn, this decrease in sulfur content will reduce airborne emissions from ships. The new sulfur regulation could change the drivers of profitability in the refining industry for many years.

Integrate solar/thermal energy in oil and gas processing

K. Gupta, M. Ethakota and S. Payyanad, January 2018

The integration of renewable energy sources into the conventional energy sector can be a promising solution to reduce plant GHG emissions. The opportunities and applications for solar/thermal systems to replace fossil fuels fully or partially are explored here.

Aggressive optimization programs are critical for the survival of marginal refiners

D. Micklem, February 2018

Increased competition from large, efficient refineries is forcing small- to mid-sized refiners to rethink their strategies to remain competitive. Aggressive optimization programs are a very attractive strategy. Marginal refiners can use advanced simulation models and software to secure returns demanded by their stakeholders. These tools and methods are low-risk approaches to value creation. With an appropriate understanding of where and how to optimize assets, these benefits can be sustained.

Use advance predictive analytics for early detection and warning of column flooding events

J. Bird, J. B. Burns, Y. Racette and J. Beaulieu, June 2018

In this study, a methodology was implemented to predict crude distillation tower flooding events based on key process variables, including product yields, column pumparound flowrates, column temperatures and overhead reflux flowrate. A logistic regression model was selected as the predictive tool due to its ability to differentiate flooding events from non-events, as well as the ease of implementation.

Surviving turbulent times requires deep management changes

J. P. Chevriere, December 2019

As with any major tectonic shift, the turbulence accompanying the shale revolution is irregular, erratic and nonlinear. Consequently, senior management must apply new business models to address the unprecedented market challenges within the energy and HPI. E&C companies must rethink their goals and strategies to return to prosperity. At present, too many E&C companies are failing. Better management of the four key factors—capital, physical assets, knowledge and time—will greatly help E&C contractors.

Circular economy: Getting in the door of opportunity ahead of a vanishing polymer market

P. Bjacek, January 2020

Up to 43% of the global conventional polymer production expected by 2040 may disappear due to circular economy initiatives. In addition, due to the growth in wind turbines and solar panels, and in lightweight composite materials in cars and planes, advanced materials waste is just beginning. As a result, oil and gas companies stand to lose up to half of demand growth; however, they may also have the most to gain. Two drivers of this significant change center on rising waste consciousness and the transition to cleaner energy sources.

Five key innovation concepts to impact frontline engineers in 2020

A. McIntee and K. Finnan, February 2020

Frontline engineers and managers represent a large cohort of people who are, and will continue to be, impacted the most by Industry 4.0 shifts and trends. These five key innovation concepts include:

1. Engineers and frontline managers must work backwards

from business goals and constraints, defining the approach and technologies to deliver outcomes, rather than starting with new technologies and looking for places to apply them
2. Understanding how solutions or decisions are made; black-box thinking (e.g., educated guesswork) is not the future
3. Decisions made with expanded support from a scalable digital twin
4. Holistic real-time actions through accessorizing
5. Experts uses for less-expert users through new user interfaces.

Shape the refinery of the future through integration

S. N. Maiti, September 2020

The article discusses various aspects of evaluating options that enable an existing refiner to make investment decisions to optimally diversify into petrochemicals through integration.

How high can PE/PP plant capacities rise?

J. D. Divey, March 2021

Consequently, ethylene cracker plants with capacities exceeding 1 MMtpy of ethylene have become the norm. Ethylene plant capacities have soared close to 2 MMtpy, which was unthinkable two decades ago. With the inclusion of multiple polyethylene (PE) and polypropylene (PP) plants to match the olefins balance, the single-line capacities of PE/PP plants have risen to 450,000 tpy–550,000 tpy. Until about 2010, PE/PP plant capacities of 300,000 tpy–400,000 tpy were considered standard for a large plant. However, PE/PP technology licensors have kept up the pace by offering capacities in the range of 450,000 tpy–650,000 tpy, depending on the product mix. This article will explore the determining factors for different premium technologies that might limit single-line capacities, as well as potential challenges for future capacity increases.

Keeping fugitive emissions costs down with low-E valves

S. Hunsicker, August 2021

Fugitive emissions have become an increasingly critical area of interest for chemical processing and refining facilities. If left unmitigated, these uncontrolled leaks can be detrimental to a facility's bottom line. This article explores some essential strategies for actively addressing fugitive emissions to help reduce leaks, maintain compliance and keep costs low.

History of the HPI—Up to 1930s: Whales, lamps, automobiles, plastics and war

L. Nichols, January 2022

Over the next 10 mos, *Hydrocarbon Processing* will provide a detailed history of the origins and evolution of the HPI. This robust analysis will chronicle the beginnings of the modern refining and petrochemical industries through the technological advancements that have created the global energy juggernaut the industry has become today. This examination of the history of the HPI will dictate how human ingenuity has provided the products that have increased the standard of living for billions of people around the world, as well as a reflection on technological advancements over the past 170 yr.

Digitally uncover profitable pathways to net-zero

S. Dubey, March 2022

As many leading energy companies commit to net-zero targets, it is important to reaffirm that good planning, execution and the capability to demonstrate additionality in abatement measures can lead to an economically viable transition to net-zero. This article builds on the following themes:

- The need for energy companies to prioritize their emissions-related initiatives based on detailed analysis of technology options, market conditions and regulations
- The digital capabilities and solutions needed by organizations to uncover this profitable path to net-zero
- A recommended framework and next steps for organizations that wish to build this capability.

Overview of decarbonization pathways for the oil and gas and petrochemical industries

J. Buehler, May 2022

This two-part article will cover the seven pathways to decarbonizing the oil and gas and petrochemical industries: green and blue hydrogen, biofuels, renewable fuels and e-fuels, the circular carbon cycle, energy efficiency, new technologies, electrification and carbon capture.

Overcome inflation and supply chain issues in construction

C. Rentschler, A. Parmar and G. Shahani, June 2022

Inflation and supply chain disruptions are not new to the construction industry, but the severe combination of these factors and the rapid pace of change driven by the COVID-19 pandemic are unprecedented. History has shown that supply shortages and increasing inflation can be sporadic events. While experience has demonstrated that the price spikes eventually subsided (in nearly all cases), contractors that were unable to pass on the price increases for an extended period were harmed. Contractors should be equipped with the knowledge and structure to fight through the inflation situations when they occur.

Evaluate options for decarbonizing petroleum refineries

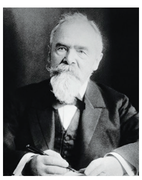
R. B. Singh, August 2022

Refiners are strategizing to align with a low-carbon future. Moving from transport fuels to petrochemical feedstocks, producing renewable fuels and sourcing low-carbon hydrogen are emerging as possible options. Governments, technology providers, refinery owners and engineering companies will all play a role in selecting and implementing the most efficient and least-disruptive pathways to a low-carbon future. One thing is certain: this transition will be gradual and require operating refineries to align product slate with demand and reduce their direct CO_2 emissions. HP

LEE NICHOLS, VP, Content/Editor-in-Chief and
SUMEDHA SHARMA, Technical Editor

Industry Pioneers: The people that have advanced the HPI for more than 150 yr

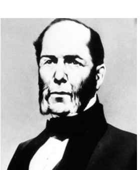
CARL VON LINDE



Carl von Linde was a German scientist and engineer who pioneered new technologies in refrigeration and the invention of air separation and gas liquefaction processes. In the 1870s, Linde's studies led to an efficient design for refrigeration. The first iteration used methyl ether, which was later switched to ammonia. Towards the end of the 1870s, Linde and five partners established the Gesellschaft fur Linde's Eismaschinen (Linde's Ice Machine Co.) in Wiesbaden, Germany. The novel refrigeration device was of extreme importance, especially to the beer brewing industry, as well as the meat industry and cold storage facilities. These inventions quickly replaced ice in many industries, especially in food handling.

In the early 1890s, Linde research shifted to low-temperature refrigeration and the liquefaction of air. This included the technique of obtaining pure oxygen and nitrogen by fractional distillation of liquefied air. In 1895, he successfully liquefied air by compressing it and then letting it expand rapidly, which cooled it. This enabled him to obtain oxygen and nitrogen from the liquified air by slow warming.[1] Several years later, he invented a method for separating pure liquid oxygen from liquid air, which provided oxygen to various industries.[2] These discoveries led to the creation of Linde Air Products in the U.S. in 1907, which later became part of the Union Carbide company at the beginning of World War I.[3]

ABRAHAM GESNER



The Canadian geologist and physician, Abraham Gesner, is credited with the invention of kerosene. In the mid-1830s, he worked as a provincial geologist in New Brunswick, Canada, examining coal in the province. In the 1840s, he began experimenting with hydrocarbons, especially bitumen from Trinidad. From these experiments, he developed a process to extract oil, which could be burned. However, the bitumen product was expensive to obtain and the burning of it produced a horrendous odor. Therefore, he started experimenting with a type of asphalt called albertite. Gessner noticed that the oil that was extracted—the process was done by heating coal in a retort[4]—burned with a strong yellow flame with no odor.

In 1854, Gesner obtained three U.S. patents for his kerosene fuel and set up the North American Kerosene Gas Light Co. on Long Island, New York (U.S.). The company prospered and kerosene began to be the go-to fuel for lamp lighting, replacing whale oil.

SAMUEL KIER

Samuel Kier was an American inventor and is thought of as the founder of the American refining industry. Several years after Gesner's discovery of kerosene, Samuel Kier began his own experimentation on petroleum that would seep into his family's salt wells near Pittsburgh, Pennsylvania (U.S.)—at the time, this substance was known as "carbon oil." Although the substance could be burned for lighting, much like Gesner's experiments with bitumen from Trinidad, the unrefined material had an unpleasant odor. Instead, Kier used the material for medicinal purposes until it lost its appeal in the early 1850s.

To find another path for the oily substance, Kier experimented with using the substance for lighting. On the recommendation of James Booth, a chemist and professor from Philadelphia, Pennsylvania (U.S.), Kier used distillation to extract the best materials for the use of lamp burning fuel. In 1851, Kier began selling his lamp fuel oil for $1.50/gal, a more cost-effective product than whale oil. As demand grew, Kier established North America's first oil refinery in 1853, which processed 1 bpd–2 bpd of liquid petroleum in its first year, growing to 5 bpd in 1854. The effects of Kier's refinery not only led Pittsburgh to become the first U.S. city to be illuminated by petroleum, but also led to the start of the country's refining industry.

MARCUS SAMUEL, SAMUEL SAMUEL

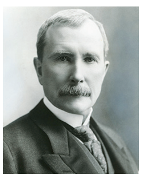
In 1870s, the Samuel brothers inherited their father's import-export business. At the time, their father (Marcus Samuel) built a prosperous business of importing shells from the Far East to be used in interior design.

Around 1880, the Samuel brothers expanded their father's business to include exporting oil around the world. However, a challenge at the time was oil containers and space on a marine vessel. Oil barrels were prone to leak and took up a lot of space on oceangoing vessels. To overcome this challenge, they commissioned a fleet of steamers to carry the oil in bulk.[5] Just as the brothers were revolutionizing crude oil trade, they began to include shipping kerosene to demand centers around the world. In 1896, the brothers renamed the company Shell Transport and Trading Co.

By the late 1890s, business was booming, and the the company established its first refinery in Balikpapan, Indonesia in 1897

(known as Dutch Borneo at the time). In 1901, Shell Transport and Trading Co. merged with a smaller competitor—Royal Dutch—that had set up a sales organization in Asia. The company took the name the Royal Dutch Shell Group. The company's operations—drilling, exploration and refining—expanded rapidly to various parts of the globe and since it has become one of the largest integrated energy companies in the world.

JOHN D. ROCKEFELLER



The American industrialist was responsible for building the largest refining operation in the U.S., which led to the spinoff of several different entities, each becoming some of the largest integrated oil companies in the world.

The company's origins began in the early 1860s. Rockefeller and other associates owned refineries in Ohio (U.S.), producing kerosene for lamp lighting. Over the next 20 yr, the company expanded exponentially, controlling nearly 95% of refining operations in the U.S. By the mid-1890s, Standard Oil Co. had also become the dominant kerosene exporter to other parts of the globe, such as Asia. However, the company was eventually labeled a monopoly and was split into several entities that would eventually lead to the creation of Amoco, Chevron, Exxon, Mobil and Marathon.

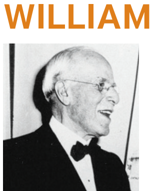
FRITZ HABER, CARL BOSCH

Using fertilizers for agricultural significantly expanded in the 1800s/early 1900s. However, the primary sources to develop ammonia—niter and guano—were not adequate to satisfy demand; therefore, a new process was needed to produce adequate amounts of ammonia and nitrates. This challenge was solved by the German chemist Fritz Haber in 1909 and later commercialized and expanded by Carl Bosch of BASF.

Haber conducted significant research in the early 1900s on the synthesis of ammonia from nitrogen and hydrogen. The process requires high temperatures, high pressure and catalysts. Intense research was led by Carl Bosch. After a few years of trial-and-error, the process was a success, and the first ammonia synthesis plant went into operations in Oppau, Germany in 1913.[7]

The Haber-Bosch process—still in use today—enabled BASF to become the first company to employ high-pressure technology. The Oppau facility's success with ammonia production expanded to include a second site in Leuna, Germany. This site would not only utilize the Haber-Bosch process to produce ammonia but would also be instrumental in the research and development of synthetic gasoline from the hydrogenation of lignite.

WILLIAM BURTON



William Burton was an American chemist who is credited for inventing a viable thermal cracking process. In 1910, he and Robert Humphreys developed their own thermal cracking process while working at Standard Oil of Indiana's Whiting refinery—Vladimir Shukhov (Russia) holds the earliest patent for thermal cracking, which he invented in 1891. However, the Shukhov Cracking Process found little adoption since lighter fractions (e.g., gasoline) did not exist at the time.

According to literature[8], Burton's thermal cracking process involved heating crude oil in a still to 371°C–399°C (700°F–750°F). The petroleum vapors were regulated through a valve system that maintained constant pressure through the entire process. Once the fractions were evaporated, they gathered through a condenser. Lastly, the still was opened and the carbon deposits were collected. The process produced primarily gasoline, gasoil, residual fuel oil and petroleum coke.[8] The Burton process was used extensively for more than 20 yr, until the creation of catalytic cracking.

HERMAN FRANCIS MARK

The Austrian-born chemist, Hermann Francis Mark, is well-known for his contributions to the development of polymer science, which he devoted more than 60 yr of his life to. While working with IG Farben in Germany, Mark worked on experiments on the commercialization of polymers such as polystyrene, polyvinyl chloride and the first synthetic rubbers.[8]

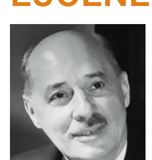
After escaping Nazi Germany, Mark found his way to the U.S. and started classes on polymers at the Polytechnic Institute of Brooklyn, later founding the Polymer Research Institute, which was the first facility devoted to polymer research. For his lifetime of work, he received the U.S. National Medal of Science in 1979.

OTTO RÖHM

Otto Röhm was a German chemist and pharmacist that founded Röhm and Hass AG. His experiments with methyl methacrylate (MMA) led to the development of Plexiglas.

After successfully developing and marketing Oropon, a more hygienic and efficient way of staining leather, Röhm focused his sights on plastics research. While working with Walter Bauer, researchers conducted an experiment polymerizing MMA between two layers of glass in a water quench. The result was a clear plastic sheet that was lighter than glass but much less prone to shatter. The material, called Plexiglas, would first be used as a substitute for glass in military aircraft, eventually being used in many industrial and commercial applications.

EUGENE HOUDRY



With the aide of E. A. Prudhomme, French engineer Eugene Houdry is known as a pioneer in catalytic cracking. After serving in WWI in the French artillery division and later in the tank corps, Houdry worked in his father's steel business, as well as raced cars. His passion led him on a pathway to improving engine performance.

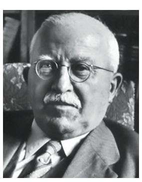
Prior to Houdry's discovery, thermal cracking was the primary refining process to produce gasoline. However, many researchers and analysts feared that thermal cracking was insufficient to satisfy increasing global demand for gasoline. Houdry and Prudhomme's research led to the development of the fixed-bed catalytic cracking unit. Operations of the 15,000-bpd unit began at Sun Oil's Marcus Hook refinery in Pennsylvania (U.S.) in 1936. Approximately 50% of the 15,000-bpd unit produced

high-octane gasoline, which was double the production of conventional thermal processes.[9] The novel process produced high-octane gasoline—the Houdry unit could produce 100-octane aviation gasoline, which provided U.S. military aircraft a significant advantage over Germany.

OTTO BAYER

While working at IG Farben in the late 1930s, German chemist Otto Bayer conducted extensive polymer research that led to the discovery of polyurethane. One such experiment created a new polymer by reacting 1,8 octane diisocyanate with 1,4 butanediol. This new polymer, polyurethane, was first used as coatings and adhesives. It was a suitable replacement for rubber during World War 2 (WW2). Post-WW2, the product was used extensively in many applications, and is still widely used today. This includes in insulation, building materials, adhesives, coatings and clothing, among others.

HERMANN STAUDINGER



The Nobel Prize-winning German chemist is best known for his research on macromolecules, which he characterized as polymers. Staudinger also discovered ketenes, which would later be used to produce antibiotics.[10]

Staudinger hypothesized that polymers were linked end-to-end. His work with high-molecular weight compounds provided the foundation for polymer chemistry. He authored hundreds of scientific papers and several books on topics such as macromolecular chemistry and biology. His research on macromolecular chemistry earned him a Nobel Prize in 1953.

WALLACE CAROTHERS

The American chemist started work at DuPont in the late 1920s. His primary focus was on polymer research. Under his tenure, DuPont would produce several long-lasting discoveries that would revolutionize the chemical industry.

In 1930, Carothers and his staff conducted experiments and research on an acetylene polymer. The goal of the research was to create synthetic rubber. After several tests, the group produced a substance that resembled rubber, which later took the name Neoprene.

Carothers' group was also credited with producing the first synthetic silk. This synthetic polymer would later be called polyester, which is still in use today.

By the mid-1930s, Carothers produced fibers comprised of amine, hexamethylene diamine and adipic acid. These new strong, elastic fibers were called polymer 6,6 (or nylon 66). Nylon first became a household product as women's hosiery, later being used in the U.S. war effort to produce parachutes and tents. Over the next several decades, nylon would be used extensively as a combined fabric in fashion and apparel, as well as in several industrial applications—the global nylon industry market size is forecast to reach more than $46 B by the late 2020s.[10,11]

ERNEST SOLVAY

The Belgian chemist and industrialist is known for developing the ammonia-soda process to manufacture soda ash on a commercial scale. The process was invented by Ernest and his brother Alfred in the early 1860s. In 1863, the brothers founded Solvay and Cie, opening their first soda ash plant in Couillet, Belgian shortly thereafter.[12]

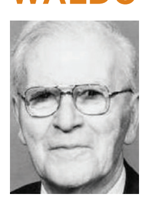
Soda ash was widely used in several industrial applications. The wide use of the material enabled the Solvay brothers to expand operations into other countries, such as Austria, Germany, Russia, the UK and the U.S. By 1900, 95% of soda ash consumption around the world was produced by the Solvay process. Many of these plants are still in use today.

CHARLES GOODYEAR

The American self-taught chemist is known for developing volcanized rubber, which revolutionized the industry. Goodyear's dive into better rubber materials began while visiting the Roxbury India Rubber Co. in New York (U.S.). After examining life vests, he believed he could improve the valves on the vests. However, the store manager made the comment to Goodyear that he would be better off inventing a better rubber.[13]

Over the next several years, Goodyear worked tirelessly on developing better rubber, even going nearly bankrupt in the process. However, while working at the Eagle India Rubber Co., Goodyear accidentally discovered the vulcanization of rubber by combining rubber and sulfur over a hot stove.[6] Once heated, the rubber hardened. In 1844, he finally perfected the process and was given a patent for his invention—the process was called vulcanization after Vulcan, the Roman god of fire.[13] His work led to the development of a vulcanized rubber producing hub in the northeast U.S., leading to the Goodyear company being named in his honor in the late 1890s.

WALDO SEMON



Waldo Semon was an American chemist whose detour with assigned laboratory research at B. F. Goodrich led to the development of vinyl—the second best-selling plastic in the world. Dr. Semon's original research project was to coat metal with synthetic rubber. However, having exhausted his possibilities with rubber, he began experimenting with synthetic polymers, including polyvinyl chloride (PVC). Dr. Semon heated the stiff polymer in a high boiling solvent, obtaining a jelly-like substance that was elastic but not adhesive. PVC was more durable than crude rubber and Semon continued experimenting with it until he finally succeeded, in his first breakthrough, in plasticizing the substance and making it highly resilient. In his second breakthrough, he succeeded in making the material moldable into different shapes, giving the world its second-most employed plastic. Goodrich commercialized this product under the trademark Koroseal,[14] making shock-absorber seals, electric-wire insulation and coated-cloth products.

Semon's success with vinyl did not deter his original research. By 1934, he had invented over 100 methods of affixing synthetic rubber to metal. He continued to lead teams of researchers to invent other families of plastics, which earned him 116 U.S. patents[15] and the Charles Goodyear medal in 1944.[16] Throughout his career, he was known for his devotion and support of science education in schools.

FREDERIC STANLEY KIPPING

Frederic Stanley Kipping was a British chemist whose pioneering work in the chemistry of silicones formed the basis of 40 yr of continued research at the interface of organic and inorganic chemistry and the commercial development and application of silicones. He was the chief demonstrator in chemistry at the City and Guilds of London Institute and later became a professor of chemistry at University College, Nottingham. Kipping's research on optically active compounds resulted in his interest and study of organic silicon compounds at Nottingham during the early 1900s. His work was published in a series of 51 journal papers and formed the basis for pioneering research that led to the development of synthetic rubber and silicone-based industries.[17] With exceptional water resistance, high-temperature stability silicones found a variety of early applications as synthetic rubber, hydrophobic coatings, greases and lubricants.[18]

JAMES FRANKLIN HYDE

Dr. James Franklin Hyde, an American chemist and inventor, is credited with the commercialization of the silicone industry. His research combines organic and inorganic chemistry and the advantages of plastics and glass to create silicones, as an advanced commercial product. Glass is silicon-based, temperature and moisture-resistant, chemically inert and dielectric, while plastics are carbon-based, strong, durable and moldable. Dr. Hyde's silicone resins exhibit a combination of resistance to water, ultraviolet light, microbial growth and thermal conductivity, while being strong and stable. The substance instantly became applicable in a variety of applications like greases, lubricants, insulators, sealants, waxes and rubbers, among others.

Dr. Hyde's research built upon Dr. Eugene Sullivan's radical idea of producing a hybrid material by combining the advantages of glass with those of organic plastics to create an array of organosilicon compounds. Dr. Hyde recognized the commercial importance of some of Kipping's observations and applied them to forge his hybrid technology. His work led to the formation of Dow Corning, an alliance between the Dow Chemical Co. and Corning Glass Works that was specifically created to produce silicone products in 1943.[19] At Dow Corning, Dr. Hyde led numerous innovations throughout the mid-20th century, with applications in industries such as automobiles, construction, aerospace, cookware and pharmaceuticals.

VLADIMIR IPATIEFF

Vladimir Nikolayevich Ipatieff was a Russian and American chemist who made significant contributions to the field of petroleum chemistry and catalysis. Ipatieff made the important discovery that chemical reactions were influenced by the walls of the container in which they were taking place. One of his noted reaction discoveries was when he found that alcohol flowing through a heated iron reaction coil caused primary, secondary and tertiary alcohols to be dehydrogenated producing aldehydes, ketones and alkenes, respectively. This reaction was absent when the same alcohol was flowing through a quartz tube. He called this phenomenon 'contact reactions,' which we now know as heterogeneous catalysis.

Ipatieff discovered that catalyst efficiency could be enhanced by dispersing catalyst particles on inert support and including small amounts of zinc or copper on the support. Most industrial reactions employ catalysts dispersed on support, along with additives or promoters. He also demonstrated that γ-alumina can function as an effective dehydration catalyst, especially in ethanol to ethylene reactions. This discovery led to the development of methods for converting ethanol to alkenes, such as butadiene, which is used in the manufacture of rubber. In the 1940s, these processes were used in the commercial production of butadiene and are still being used today.

Ipateiff made another seminal innovation in chemistry by developing high-pressure autoclaves, often referred to as 'Ipatieff bombs.'[8] He published more than 300 research papers and received more than 200 patents.[22]

HERMAN PINES

Herman Pines was a Polish-American chemist whose work in understanding the chemistry of hydrocarbons and catalysis laid the groundwork for producing high-octane fuels. Paraffins were considered inert substances, with little or no reaction affinity. His research led to the development of processes for paraffin isomerization, aromatic alkylation and base-catalyzed organic reactions. Pines developed a method for catalytic conversion of paraffins, such as n-butane to isobutane. He also demonstrated low temperatures catalysis by successfully reacting isobutane with olefins in the presence of sulfuric acid as a catalyst at low temperatures. The combination of isomerization and alkylation proved to be the breakthrough in developing high-octane fuel initially for aviation and later commercialization in 1941.[23]

Pines joined UOP in 1930, which began his long collaboration with Dr. Vladimir Ipatieff.[24] They worked on understanding complex reactions affected by temperature, acid concentration and ratio of acid relative to other compounds. Pines used pure hydrocarbons in his research instead of petroleum fractions to understand mechanisms for dehydration of alcohols on alumina, aromatization of alkanes, hydrogen transfer reactions in aromatic hydrocarbons and several other acid and base catalyzed hydrogenation, aromatization and dehydrogenation reactions. Pines' research team studied a variety of transformations, including polymerization, alkylation, cyclization, additions, eliminations and hydride transfer reactions. Upon leaving UOP in 1953, he continued working on understanding and describing hydrocarbon reaction mechanisms and heterogenous catalysis at Northwestern University as the Ipatieff Professor. He published nearly 265 scientific papers and received 145 patents.[23]

VLADIMIR HAENSEL

Vladimir Haensel was an American chemical engineer most known for his invention of the Platforming process—a platinum catalyzed process for reforming hydrocarbons into gasoline. In 1947, he demonstrated that 0.01 platinum on alumina can be used as a stable, active and effective catalyst with long life and high in situ regeneration efficiency.[25] Platinum on alumina functioned as a dual-functional cata-

lyst, where platinum provides excellent hydrogenation and dehydrogenation activity and the unsaturated hydrocarbons formed could be isomerized to rings on the acidic alumina. Associated major process advantages were a high yield of hydrogen, a valuable and environmentally friendly product aiding sulfur removal and high yield of aromatics, valuable for downstream plastics and petrochemicals industries.

Haensel's method for producing high-octane fuel eliminated tetraethyl lead as an anti-knock additive; made transportation fuel efficient, cheaper and environment friendly; and replaced toxic coal tar processing by generating an aromatics pool for the plastics industry.

J. R. WHINFIELD AND J. T. DICKSON


John Rex Whinfield (left) and James Tennant Dickson (right) investigated thermoplastic polyesters while working in the laboratories of the Calico Printers' Association Ltd. from 1939–1941.[27] They produced and patented the first polyester fiber in 1941, named Terylene, which equaled or even surpassed the toughness and resilience of nylon.

DONALD L. CAMPBELL, EGER V. MURPHREE, HOMER Z. MARTIN AND CHARLES W. TYSON




Donald Campbell, Eger Murphree, Homer Martin and Charles Tyson—often called the 'Four Horsemen'—are credited with the landmark invention of fluid catalytic cracking (FCC). The FCC process revolutionized the refining industry by providing an efficient process to increase the yield of high-octane gasoline from crude oil. Their invention was awarded a U.S. patent and described as 'a method of and apparatus for contacting solids and gases.'[30]

During the late 1930s, Exxon Research & Engineering Co. (ER&E) was looking for ways to improve high-octane gasoline yield. Chemical engineering professors at MIT—Warren K. Lewis and Edwin R. Gilliland—suggested that a low-velocity gas flow through a powder may lift it enough to cause it to flow like a liquid.[1] Campbell, Martin, Murphree and Tyson at ER&E focused on the idea of a fluidized catalyst to innovate a design that would ensure a steady and continuous cracking operation. This idea led the four inventors to design a fluidized solids reactor bed with a pipe transfer system between the reactor and regenerator unit in which the catalyst is decoked and regenerated for reuse. The solids (catalyst) and gases (vaporized oil) are in continuous contact as they move upward in fluidized flow while cracking occurs. The hydrocarbon chains are split into smaller pieces, and the cracked molecules are further distilled to produce gasoline, heating oil, fuel oil, propane, butane and chemical feedstocks that are instrumental in producing a variety of petrochemical products.

The four inventors developed the process in 1942, and the first commercial FCC facility went online on May 25, 1942.[31] Their invention was not only extremely important but also timely, as it enabled refineries to produce and supply enough high-octane fuel to aid U.S. and Allied forces during World War 2 (WW2). FCC technology also led to the rapid buildup of butadiene production, which was used by ER&E for making synthetic butyl rubber, another technology that was vital during that era. The first commercial FCC plant processed 13,000 bpd of heavy oil, making 275,000 gal of gasoline.[32] FCC is widely employed today around the world and continues to evolve as the market for high-performance clean fuel demand increases.

ROBERT BANKS AND PAUL HOGAN


American research chemists J. Paul Hogan and Robert Banks discovered crystalline polypropylene (PP) and created a process for making high-density polyethylene (HDPE) while working at Phillips Petroleum in 1951.[35] Their breakthrough invention, although serendipitous, was not accidental. In the wake of WW2 and diminishing oil demand, Phillips Petroleum was involved in concerted efforts to investigate the uses of natural gas liquids (NGLs). Hogan and Banks were studying processes by which propylene and ethylene could be converted to valuable gasoline-like materials, so they started investigating the use of catalysts to do so.

In June 1951, they were experimenting by adding a small amount of chromium oxide to a nickel oxide catalyst and fed propylene with a propane carrier through the catalyst-packed tube. While pure nickel oxide yielded the expected product of low-molecular weight hydrocarbons, the chromium-modified catalyst produced a white solid—a new material, crystalline PP. With this new discovery, they pivoted research efforts from gasoline to plastics and used the chromium catalyst to produce an ethylene polymer. Within a year, they created the process for making HDPE—the safest, hardest and most heat-resistant plastic created at the time using much lower operating pressure than branched low-density PE. Phillips launched their product as Marlex® in 1954.[36] Their invention revolutionized the consumer plastics industry and launched Phillips, an oil company, as a manufacturer of polyolefin plastics. HDPE is extensively used in packaging, commodity plastics, toys, tools, furniture, auto parts and a variety of other applications.

Hogan received the Pioneer Chemist Award and is credited with 52 U.S. patents.[37] Hogan and Banks together received the Perkin Medal in 1987, the Heroes of Chemistry award by the American Chemical Society in 1989 and were inducted into the National Inventors Hall of Fame in 2001.[38]

KARL ZIEGLER

In 1953, German chemist Karl Ziegler employed a catalyst consisting of a mixture of titanium tetrachloride and an alkyl derivative of aluminum to create a high molecular weight, high melting point and straight-chain PE. His pioneering research with organometallic compounds, which made industrial production of high-quality PE possible, won him the 1963 Nobel Prize in Chemistry, which he shared with Giulio Natta.[39]

Ziegler's research established new polymerization reactions; enabled the syntheses of durable, higher melting, unbranched polymers; and laid the groundwork for several useful industrial processes. He combined classical organic chemistry with physical and analytical experimental methods in his phenomenal work on polymerization reactions.

Ziegler began his work on carbon compounds and organometallic chemistry during his professorship at the University of Heidelberg, which he continued after joining as the Director of the Max-Planck-Institut in Mülheim in 1943.[40] Between 1952 and 1953, Ziegler's research group tested various organoaluminium compounds and discovered that nickel was the cause of the chain-ending reaction. They further investigated to find a reagent to suppress this chain termination reaction, which led them to discover that titanium, under mild atmospheric conditions, produced rigid, high-melting unbranched PE.

Besides his work with organometallic compounds, he is also known for his research in the field of radicals with trivalent carbon and synthesis of multi-membered ring systems, which earned him the Liebig medal in 1935.[40] One of the many awards Ziegler received was the reputed Werner von Siemens Ring in 1960 for expanding the scientific knowledge of and the technical development of new synthetic materials.[39] Ziegler was able to take his discovery to industrial markets. By 1958, he was reaping the benefits of approximately two dozen licenses.[41]

GIULIO NATTA

Giulio Natta, an Italian scientist and chemical engineer, extended Ziegler's method to other olefins. Based on his own findings on the reaction mechanism of polymerization, he developed further variations of the Ziegler catalyst. For his contribution to the field of high polymers, he shared the Nobel Prize in Chemistry with Karl Ziegler in 1963.[42] Commercial Ziegler-Natta catalysts include many mixtures of halides of transition metals, especially titanium, chromium, vanadium and zirconium, with organic derivatives of nontransition metals, particularly alkyl aluminum compounds.[43]

Natta's early research career focused on studying solids by x-rays diffraction (XRD) and electron diffraction. He later employed the same expertise to study catalysts and the structure of high organic polymers. By 1938, he began investigating macromolecules—polymerization of olefins and the kinetics of subsequent concurrent reactions.[44] In 1953, after he received financial aid from the large Italian chemical company Montecatini, he extended Ziegler's research on organometallic catalysts to stereospecific polymerization.[44] These studies led to the development of isotactic PP, a thermoplastic polymer of highly regular molecular structure with commercially important properties of high strength and a high melting point. In 1957, Montecatini produced this polymer on an industrial scale at their Ferrara plant.[44] Natta's creation was commercially marketed as a plastic material by the name of Moplen, as a synthetic fiber by the name of Meraklon, as a monofilament by the name of Merakrin, and as packing film by the name of Moplefan.[44]

Natta discovered new classes of polymers and used XRD to determine the exact arrangement of chains in the lattice of the new crystalline polymers he discovered. He created polymers with sterically ordered structure—isotactic, syndiotactic and di-isotactic polymers and linear nonbranched olefinic polymers and copolymers with an atactic structure.

Natta is also known for his later research that led to two different routes for the synthesis of new elastomers: by polymerization of butadiene into *cis*-1,4 polymers with a high degree of steric purity, and by copolymerization of ethylene with other a-olefins (propylene), originating extremely interesting materials such as saturated synthetic rubbers.

HERMAN SCHNELL

Dr. Hermann Schnell was a German scientist at Bayer who discovered the synthesis reaction of a new plastic—polycarbonate from co-monomers bisphenol A and phosgene. The new thermoplastic polymer—polycarbonate—has superior strength, toughness and impact resistance. Despite its resistance to breaking and splintering, it is lightweight, mostly optically transparent and can be easily molded or thermoformed. Unlike most thermoplastics, it can undergo large plastic deformations without cracking or breaking. With these properties, it is used in a variety of daily applications such as construction materials; electronic, auto, aircraft and security components; and optical lenses.[45]

Schnell studied under Nobel laureate and chemist Herman Staudinger. Soon after graduating, he joined the research and development department at Bayer AG, Leverkusen, Germany. Shortly thereafter, he moved to the lab at Uerdingen where he and his research team discovered the synthesis reaction of polycarbonate. The official patent for polycarbonate synthesis was granted in 1953 and was registered under the brand name Makrolon® on April 2, 1955.[46] Bayer started industrial-scale production of Makrolon® at its plant in Uerfingen, Germany in 1958.[46]

Schnell became the department leader at Bayer research at just 36 yr of age and was appointed department head of Bayer's entire central research facility in Leverkusen in 1971. He retired from Bayer in 1975.[46]

FREDERICK W. STAVELY

Frederick W. Stavely was a chemical research scientist who is credited with the discovery of polyisoprene. Stavely was a researcher at the Firestone Tire & Rubber Co in 1953 where, while investigating the reaction of butyl lithium on butadiene, he discovered that the polymerization of isoprene with metallic lithium produced polyisoprene with high *cis* content. High *cis* content is indicative of enhanced strain crystallization, which is closer to natural rubber, also with high *cis* content. This discovery was important during WW2 because other synthetic compounds did not exhibit the crystallization effect that was achieved in Stavely's process. Stavely served as Chairman of the American Chemical Society Rubber Division. In 1972, Stavely received the Charles Goodyear Medal in recognition of this discovery.[48]

EDITH MARIE FLANIGEN

Edith Marie Flanigen, an American chemist, is known for her synthesis of zeolites for molecular sieves. Molecular sieves are crystalline microporous structures with large internal void volumes and molecular-sized pores that can separate or filter complex mixtures, as well as function as

catalysts for chemical reactions. These compounds find numerous applications in the refining and petrochemical industries.

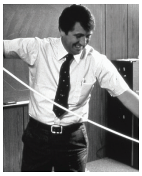
Flanigen joined Union Carbide in 1952 and began working on molecular sieves in 1956.[49] During her 42-yr career at Union Carbide and UOP, Flanigen invented or co-invented more than 200 novel synthetic materials but is best known for her substantial contributions to the development of zeolite Y, an aluminosilicate sieve used to make oil refining more efficient, cleaner and safer.[50] Zeolite Y is essentially employed in the cracking of crude oil to produce commercially valuable products like gasoline and diesel in a cleaner and more efficient manner. Her invention finds application in purification and contaminant removal and can be used to make ethylene and propylene, which are important raw materials to the petrochemical industry.

Besides her work on molecular sieves, Flanigen co-invented a synthetic emerald and pioneered the use of mid-infrared spectroscopy for analyzing zeolite structures. She has been quoted to say that one of her strengths throughout her career has been her ability to discover new material and see it through to commercialization, from envisioning processes for manufacturing it on a large scale to developing it for industrial application.

Flanigen became the first woman to hold the position of Senior Corporate Research Fellow at Union Carbide in 1982. She retired in 1994 with 108 U.S. patents in the field of petroleum research and product development.[50,51]

In 1992, she became the first woman to receive the prestigious Perkin medal, the most distinguished honor in applied chemistry.[22] Flanigen was the recipient of the $100,000 Lemelson-MIT Lifetime Achievement Award in 2004 and was inducted into the National Inventors Hall of Fame in the same year.[22] In 2014, President Obama presented Flanigen with the National Medal of Technology and Innovation for her contributions to science and technology.[51]

ROBERT WALTON GORE



Robert W. Gore was an American engineer, inventor and entrepreneur who is best known for his breakthrough invention of expanded polytetrafluoroethylene (ePTFE). Gore's discovery that PTFE could be transformed into an entirely different physical state led to a phenomenally new direction in material science, resulting in commercially well-known products such as GORE-TEX fabric, a water-resistant and breathable fabric known for its applications in sporting and outdoor activities. Several important products have grown from ePTFE such as new electrical cables, industrial filters, medical implants, textiles woven from ePTFE fiber for space exploration, laminated fabrics for outdoor activities, emergency response, defense and ELIXIR guitar strings.

Gore's father was a Dupont employee and he often experimented with DuPont materials in his basement exploring new ways to use them. While he was a sophomore at the University of Delaware in 1957,[52] Gore helped his father develop a successful process to use PTFE to insulate multiple copper conductors to create the ribbon cable, a product highly applied in the growing computer industry. Gore's process resulted in the product MULTI-TET cable and led his family to found W.L Gore & Associates in 1958,[52] operating from the basement of their home. The company expanded its capacity with the growing demand and applications of MULTI-TET and TETRA-ETCH, a pipe thread tape, and Gore earned his first patent as the inventor. After completing his doctorate in chemical engineering, he joined W.L. Gore & Associates as the technical and research leader. In 1969, while researching a process for stretching extruded PTFE into pipe-thread tape, he discovered that the polymer could be expanded. Gore's discovery of ePTFE resulted from a 'frustrated hard yank' after a series of failed experiments to stretch heated rods of PTFE by 10%. This serendipitous discovery was that instead of slow stretching, the application of a sudden accelerating yank stretched the PTFE by 800%, creating a microporous PTFE that was 70% air.

Gore's earned nine patents for his phenomenal work with fluoropolymers and was elected to the National Academy of Engineering in 1995 for his technical achievements.[53] He was also awarded the highest award in the United States designated for an industrial chemist, the Society for Chemical Industry's Perkin Medal in 2005 and the 2003 Winthrop-Sears Medal, from The Chemists' Club and the Chemical Heritage Foundation, now the Science History Institute.[53]

CHARLES PLANCK AND EDWARD ROSINSKI

Charles J. Plank and Edward Rosinski invented a zeolite catalyst for catalytic cracking that revolutionized the petroleum industry by increasing the yield of gasoline by 40%[54] from every barrel of oil run through a catalytic cracker. Thermal cracking, or the application of heat to petroleum, is the process by which the larger molecules "crack" or break down to form simpler molecules like those found in commercially useful products like gasoline. Plank and Rosinski, while researching catalysts for Mobil Oil (now ExxonMobil) in the 1950s,[55] idealized the use of porous clay-like zeolites that bear microscopic channels close to the hydrocarbon length as catalysts for petroleum cracking. In 1961, it was discovered that certain crystalline zeolites could be combined into a binder and converted into a super-efficient cracking catalyst.[54] Zeolites present superior activity and selectivity at low severity, resulting in significantly high gasoline yield. Moreover, the increased yields are obtained without increasing gas or coke formation, the undesired byproducts of cracking. With higher efficiency and fewer process risks than traditional methods during those times, their process marked a major step forward for the petrochemical industry.

In July 1960, Plank and Rosinski's patent "Catalytic Cracking of Hydrocarbons with a Crystalline Zeolite Catalyst Composite" was submitted and was officially patented on July 7, 1964. Mobil named it "Zeolite Y" and used it in commercial processes in 1964.[55] Through the mid-1980s, nearly 35% of U.S. gasoline was being produced via zeolite catalytic cracking.[55]

Today this catalyst, the first containing crystalline zeolite, is extensively used in all cracking units in the U.S. and around the world. Although catalysts had long been used in oil refining, Plank and Rosinski's catalyst made a significant impact on the efficiency of the cracking process and provided a remarkable increase in gasoline yield from crude oil.

Charles J. Plank was born in Calcutta, India and later moved to Lafayette, Indiana. In 1936, he received a BS degree in mathematics, chemistry and physics from Purdue University.[5] He later

earned an MS degree and in 1942, he received his Ph.D. in physical chemistry from Purdue University.[56]

In 1941, Plank joined the research department of Socony-Vacuum Oil Company, the predecessor of Mobil Oil Corporation. He was promoted as a senior scientist in 1970,[55] the highest scientific post, at Mobil's Research and Development Laboratory. Throughout his career as a scientist and technologist, he was awarded 83 U.S. patents and several hundred in other countries.[56]

Edward Rosinski was born in Gloucester County, New Jersey and aspired to be a chemical engineer while still in high school. Upon graduating in 1939, he joined the Vacuum Oil Company as a petroleum engineer.

In 1972, he was promoted to senior research associate, the company's second-highest scientific post. Rosinski was awarded 76 U.S. patents, of which many were in the field of zeolite catalytic technology.[57]

Rosinski and Plank's paper published in the journal *Industrial and Engineering Chemistry* was voted as one of the 12 most important papers published in the journal.[55] In 1979, Plank and Rosinski were inducted as the 30th and 31st members of the National Inventors Hall of Fame for US Patent No. 3,140,249, "Catalytic Cracking of Hydrocarbons with a Crystalline Zeolite Catalyst Composite."[55]

ALBERT AMATUZIO

Albert Amatuzio was a passionate flyer and a visionary who invented the first synthetic motor oil under his company's name Amsoil Inc. while still serving as a squadron commander of the Air National Guard. His invention brought synthetic lubrication to the automotive market and changed both the automotive and lubrication industries forever.

Amatuzio's entrepreneurial bent surfaced at a young age as he devised several small ventures to support his family during the Great Depression, but his passion for flying led him to join the Naval Corps and then the Merchant Marine. In the post-war period, Amatuzio joined the Air Force, earned his wings and after a hiatus due to family reasons, joined the Duluth unit of the Air National Guard. He served as a fighter pilot for 25 yr and then as a squadron commander. He was honored as the country's top pilot, winning the prestigious William Tell Air-to-Air Shootout competition and the Earl T. Rick Competitive Shootout.[58]

As a pilot, he gained knowledge about how jet engines survived on synthetic oil and envisioned that the same could be applied to other vehicles and equipment that people used in their daily lives. He believed that the same performance benefits would prove invaluable to cars, trucks and other combustion engines. Oil quality during those times was poor—with problems of low heat resistance, contribution to hard-start during cold weather and adverse effects on engine life and performance. He reasoned from his experience that only synthetic oils could avoid these adverse effects and improve engine performance.

Amatuzio's ideas seemed radical and unnecessary at that moment. "They all thought I was at altitude too long without oxygen," Amtuzio joked about his skeptics.[58] However, with his unmatched resilience and tenacity, he dismissed the doubters and began his research and development efforts in 1963.[58] By 1966, he formulated the first synthetic motor oil and founded his company Amsoil.[59] In 1972, Amsoil's tagline 'The First in Synthetics®' was launched as AMSOIL 10W-40 Synthetic Motor Oil became the world's synthetic motor oil to meet American Petroleum Institute's requirements.[59]

Amatuzio had changed the course of the entire automotive lubricant industry. His relentless efforts to bring the best choice to consumers led him to make AMSOIL a technological leader and create the AMSOIL dealer network. His product had met a lot of criticism for being unnecessary, disruptive and "fake," but the founding of the dealer network in 1973 conveyed the benefits of synthetic lubes to consumers.

In 1994, he was honored as the pioneer of synthetic lubrication and inducted into the Lubricant's Hall of Fame.[60] He received the Natchman Award from the Independent Lubricant Manufacturers Association. A community man and a great philanthropist, Amatuzio is remembered through the Albert J. Amatuzio Research Center. The center located in Duluth Depot outlines local service history and includes photographs, journals, stories and biographies of veterans from northeastern Minnesota who served this nation from the Civil War through Iraq and Afghanistan.[60]

STEPHANIE L. KWOLEK

Stephanie Louise Kwolek, an inductee to the National Inventors Hall of Fame and National Women's Hall of Fame, created the first family of synthetic fibers of exceptional strength and stiffness. Kwolek spearheaded the discovery, processing and development of high-performance aramid fibers. Kevlar, the best-known member of this class of fibers, is widely used in more than 200 applications, including protective bullet-proof vests, boats, airplanes, mooring ropes and fiber-optic cables and canoes.

Kwolek was born in New Kensington, Pennsylvania and was encouraged by her naturalist father to develop an early love for nature, math and science. She pursued a BS degree in chemistry from the Carnegie Institute of Technology and wanted to make a career in medicine.[61] She joined DuPont as a researcher at the textile fibers laboratory aspiring to save money for medical school. However, her research focusing on creating stronger and stiffer fibers was extremely challenging and interesting and led to her decision to make chemistry a lifetime career.

Kwolek was working on developing high-performance fibers for extreme applications when she discovered that under certain conditions a large number of molecules of rod-like polyamides line up to form liquid crystalline solutions, which can be spun directly into oriented fibers of very high strength and stiffness. With this breakthrough came the development of Kevlar in 1965, the most acclaimed product of her research—a polymer fiber five times stronger than the same weight of steel and her discovery of a new branch of polymer science—liquid crystalline polymers.[61] Her other noteworthy contributions include a low-temperature (0°C–40°C) condensation process for synthetic fibers.[61] Unlike the conventional melt condensation polymerization process used in preparing nylon, which was typically done at more than 200°C, the new lower-temperature polycondensation processes employed very fast-reacting intermediates, making it possible to prepare polymers that cannot be melted and only begin to decompose at temperatures above 400°C.

Kwolek received over 17 U.S. patents, including one for the spinning process for aramid fibers and five for the prototype

from which Kevlar was created in 1965, and won many awards for her invention of Kevlar fiber technology.[62] She was inducted into the National Inventors Hall of Fame in 1994, received the American Innovator Award in 1994, National Medal of Technology in 1996, the Perkin Medal in 1997 and the Lemelson-MIT Lifetime Achievement Award in 1999.[62] In 2003, she was inducted into the National Women's Hall of Fame.[10]

She retired in 1986 but continued to consult for DuPont and served on the committees of the National Research Council and the National Academy of Sciences.[63]

Kwolek continued to mentor women scientists and contributed to science education for young children. One of Kwolek's most cited papers, co-authored with Paul W. Morgan, is "The Nylon Rope Trick" (*Journal of Chemical Education,* April 1959, 36:182–184).[61] It describes a demonstration of condensation polymerization in a beaker at atmospheric pressure and room temperature—which is now a common demonstration in classrooms across the nation. In 2013, Edwin Brit Wyckoff published a childrens' book telling her story as: *The Woman Who Invented the Thread That Stops the Bullets: The Genius of Stephanie Kwolek.*[61]

NATHANIEL WYETH

Nathaniel C. Wyeth was an American engineer and inventor who is credited with the invention of one of the most convenient and readily recyclable plastic products today—the plastic soda bottle. Wyeth invented or co-invented about 25 products and processes in plastics, textile fibers, electronic and mechanical systems.[64]

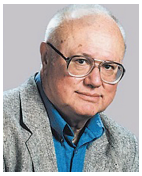
Nat Wyeth was born in Chadds Ford, Pennsylvania, into a family of artists but displayed an early interest in engineering by disassembling clocks and using their parts to make model speedboats, cutting up tin cans and soldering the pieces to make universal joints, and so on. His family recognized the budding inventor's interest and encouraged him. He followed his interests to choose the University of Pennsylvania for its engineering program. During college, Wyeth built a 20-ft-long hydroplane boat that could reach speeds of 50 mph, resting on two pontoons and powered by a Ford V-8 engine.[65] He joined General Motors upon graduation but soon chanced upon an opportunity to work as a field engineer for DuPont Corporation.

During his early days at DuPont, Wyeth excelled by inventing a plug-proof valve for the production machine and was transferred to the mechanical development lab. One of the first machines he designed was for the automatic manufacture of dynamite cartridges, which saved workers from exposure to poisonous nitroglycerin powder. Another notable invention was a machine bearing magnetized rollers, employed in the manufacture of a non-woven polypropylene fabric, Typar®.[64]

By 1967, Wyeth started working on his best-known invention, which began with his curiosity as to why plastic was not used for carbonated beverage bottles.[65] Wyeth was aware that the fabrication process created weak spots in plastic containers, and they were therefore incapable of withstanding carbonation pressure. He took to hands-on experimentation to discover ways to make stronger plastic containers. He knew that stretching out nylon thread strengthened it by forcing its molecules to align. His challenge was to stretch plastic such that its molecules would align in two dimensions, rather than just one—biaxially. He succeeded in doing this by creating a preform mold for the bottle, which resembled a test tube with screw threads running in a diamond criss-cross pattern, instead of single spiral.[64] As the plastic was extruded through this mold, the molecules aligned biaxially—just as Wyeth had intended. The criss-cross flow lines reinforced themselves, creating a uniformly strong product. He also replaced the polypropylene that was used typically for plastic bottles with polyethylene-terephthalate (PET), a polymer with superior elastic properties. He had created a petrochemical product that was light, clear, resilient, safe and eminently recyclable and laid the groundwork for future process developments in preforming, extrusion and manufacture of biaxially oriented polymer products.

Wyeth patented his process in 1973 and though recycling was not an avid idea that that time, the first PET soda bottle went into recycling soon in 1977.[64] Today, recycled PET is widely used as synthetic fiber with a major part of it used in making polyester carpets: nearly half of the polyester carpet made in the U.S. today come from recycled PET bottles.[66]

RICHARD E. MORLEY



Richard Morley was an American mechanical engineer and is considered one of the 'fathers' of the programmable logic controller (PLC). Morley designed the first PLC with his team Mike Greenberh, Jonas Landau and Tom Boissevain and called it 084, as it was their 84th project at Bedford Associates.[67] The introduction of PLCs kicked-off the 3rd industrial revolution, leading to the development of an entire industry of digital control solutions.

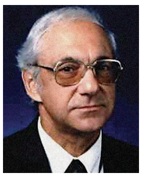
In 1964, when Morley was unemployed and working in uninteresting design jobs, he decided to pursue his interest in engineering by starting his own consulting firm with his friend Geogre Schwenk under the name Bedford Associates. Initially, they worked with machine tool firms to help them transition into solid-state manufacturing. Eventually, Morley realized that the projects he worked on were similar and work became monotonous. He decided to use his creativity and engineering acumen to invent a controller that would automate industrial processes with multiple input/output arrangements in real-time and replace hard-wired relay controls.

During those times, manufacturing facilities were operated by relay control systems. Control rooms were large with walls full of relays, terminal blocks and wired connections. The main challenges were a lack of flexibility to make process changes and the extensive time required to adjust these changes. Morley managed to design the functions of a PLC that offered advantages of uninterrupted processing, flexibility, fast reaction time and direct mapping into memory—revolutionizing manufacturing process control. The PLC was designed to be robust under severe temperature and moisture conditions and used large metal fins to transfer out air, keeping electronics dirt free. The product was capable of operating as a modular digital controller and was hence named Modicon, a brand now owned by Schneider Electric.[68]

Morley has been widely recognized in numerous publications and awards from the International Society of Automation, Instrumentation, Systems, and Automation Society, the Franklin Institute, the Society of Manufacturing Engineers and the Engineering Society of Detroit.[69] He was also inducted into the Manu-

facturing Hall of Fame. The Society of Manufacturing Engineers offers the Richard E. Morley Outstanding Young Manufacturing Engineer Award for outstanding technical accomplishments in the manufacturing profession by engineers aged 35 and under.[69]

ODO JOSEF STRUGER



Odo J. Stuger, an Austrian engineer and scientist, is recognized as the pioneer of modern-day automation and shares the credit as 'father of PLC' alongside Richard Morley. During 1958–1960,[70] Sturger led his engineering team at Allen-Bradley in developing the programmable logic controller and also coined the acronym PLC for programmable logic controllers. Allen-Bradley became the pioneering leader in programmable logic controllers in the U.S., and PLC remains a registered trademark of the Allen-Bradley Company (now Rockwell Automation).

Struger's work on PLCs was built upon the concepts studied in his doctoral research in "The process for quantitative handling of positioning errors in numerical control machines," at Vienna University of Technology.[70] His invention proved to be a 'rugged industrial computer' that, through precise numerical control of machinery, soon became ubiquitous in manufacturing environments across the world.

Struger was born in Carinthia, Austria, and studied at the Vienna University of Technology. In 1958, he moved to Milwaukee, Wisconsin (U.S.) to work as a research engineer at Allen-Bradley. Struger grew within the company and held the position of Vice President of technology until retirement in 1998.[70] He was associated with the development of the National Electrical Manufacturers Association (NEMA) standard for PLCs and IEC 1131-3 programming language standard. Struger has 50 patents to his credit in the U.S. and Canada. He received the Prometheus Award in 1996, authored more than 40 technical papers and is an inductee to the Automation Hall of Fame at the Chicago Museum of Science and Industry. To honor Struger's legacy, Rockwell Automation established the Odo J. Struger Automation Award for future engineers' exceptional advancements in the control and automation fields.[71]

JOHN MOONEY AND CARL D. KEITH

John Mooney, an American chemical engineer, and Carl D. Keith, a chemist, created the three-way automotive catalytic converter while working at Engelhard Corporation in 1973 and solved a major environmental problem—making automobile exhaust 98% cleaner.[72] An EPA report recognized this invention as one that helped save 100,000 lives and prevent many more cases of lung and throat ailments.[73] Today, catalytic converters are the key-emissions control components in automobiles worldwide.

The earliest catalytic muffler was developed by Eugene Houdry as a generic device that could convert carbon monoxide (CO) and unburned hydrocarbons (UHCs) from automobile and industrial exhausts. Houdry launched his company Oxy-catalyst and his catalytic converter design was patented in 1962.[74] However, fuel still contained tetraethyllead (TEL) as an anti-knock agent, which poisoned the catalyst in the converter. It took the passing of the Clean Air Act in 1970 and the ban of TEL for converters to be recognized and become a piece of standard equipment in automobiles.

Mooney and Keith, while working at Engelhard Corporation (acquired by BASF in 2006)[75], developed the three-way catalytic converter, where the exhaust gas components are UHCs, and CO are oxidized and nitrogen oxides (NO_x) are reduced to water, nitrogen and carbon dioxide (CO_2). The inherent complexity of the reaction implied the need for a bulky two-stage converting system. Mooney, however, theorized that if the fuel-to-air ratio was correct, the exhaust would provide just the right amount of oxygen for a one-stage converter to treat all three pollutants at once.

Equipped with his idea and a 'can-do' attitude, Mooney garnered his supervisor Keith's support to allow him to convince auto manufacturers to include an oxygen sensor to their engines. The sensor was intended to monitor fuel-to-air ratio at a level where the one-stage converter could function successfully. Volvo agreed to the proposal and soon the sensors were successfully incorporated into other automobiles, as well. The converter is a small can-shaped device that installs at the exhaust pipe under vehicles. A combination of rare-earth oxides and base metal oxides along with platinum and rhodium were used together in the catalyst. The engine exhaust passes over a specialized honeycomb-shaped structure, where a washcoat of catalyst materials acts as active sites for reactions. The design ensured an adequate amount of oxygen was offered for the oxidation and allowed all three pollutants to be targeted at once.

Both Keith and Mooney received the 2001 Walter Ahlstrom Prize and earned the National Medal of Technology in 2002 for their invention.[75] Engelhard (now BASF) continues to lead the development of automotive emissions catalysts.

MARGARET WU

Margaret Wu is an industrial chemist who is known for the remarkable contributions she has made in the field of synthetic lubricants. Her research altered the way that automobile and industrial lubricants are designed and synthesized, producing products that provide superior machine protection, high efficiency and reduced waste oil. Wu trained as a chemical engineer at the National Taipei University of Technology in Taiwan and earned a doctorate in physical chemistry in Rochester. She joined Mobil in 1977 and in the mid-1980s began developing a new class of polyalphaolefin (PAO), a synthetic base oil used in synthetic lubricants.[76]

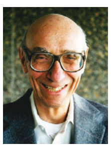
Wu attributed the 'novelty' of the synthetic lubricants she developed to their elegant chemical architecture, which is assembled in a uniform manner without extraneous side branching—earlier versions of synthetic lubricants had chemical structures with extensive side branching. In addition to lubricating properties, Wu's series of new PAO synthetic base oil demonstrated greater wear prevention, heat resistance, oxidative stability and less friction in formulated products. This provided much-improved engine performance, oil life and overall fuel efficiency in addition to reduced engine wear and waste oil.

Today, lubricant products based on Wu's work are used in a wide array of applications such as commercial vehicles, car en-

gines, industrial machinery and wind turbines.[76] Besides being a trailblazing industrial chemist who has contributed significantly to advanced synthetic lubricants, she has pioneered as one of the first women to work in this field. When she joined Mobil, she was one of only three women chemists with doctorate degrees.

She held the position of Senior Scientific Adviser, the first woman to achieve this position, which is the highest technical rank in her company. Over the course of her career, Wu earned more than 100 patents. Post-retirement, she continued as an emeritus and consultant until 2016 and was inducted into the National Inventors Hall of Fame in 2022.[77]

IRWIN M. LACHMAN, RODNEY BAGLEY AND RONALD M. LEWIS



Irwin Lachman, Rodney Bagley and Ronald M. Lewis—a team of researchers working at Corning Glass Works Co.—invented the ceramic substrate inside catalytic converters. Their work was instrumental in developing efficient, feasible and the first-ever mass-produced automotive catalytic converters.

Catalytic converters are devices that convert combustion products in automotive exhaust to less environmentally polluting components. Their research was a response to the Clean Air Act of 1970 that aimed to reduce pollutants from automotive exhausts by 95%. The team's invention enabled the automotive industry to meet these standards set by the Clean Air Act.[78]

Lachman, Bagley and Lewis used cellular ceramic technology to create the ceramic honeycomb that became the essential core component of catalytic converters. The team worked to develop a new ceramic material to achieve the key characteristics needed: high-temperature durability, low thermal expansion, low thermal conductivity at high temperatures, light weight and controlled porosity.

Lachman identified that ceramics could be ideally suited to meet the demands of the application. Their work leveraged the superior resistance of ceramic materials to dynamic and extreme temperature fluctuations and provided a well-designed surface for catalytic conversion of combustion products. Ceramics offer the unique property of very low thermal expansion, making them extremely resistant to thermal shock, which is a necessary requirement for durability.

Lewis discovered that inducing the proper preferred orientation of crystallites in the substrate is key to achieving low thermal expansion, thus high resistance to extreme temperature fluctuations. Ceramic also provides a textured surface for the catalyst, is phase stable, resistant to corrosion and can withstand very high operating temperatures.

Bagley developed the process and the extrusion die to make thin-walled, honeycombed cellular ceramic substrates. The design consists of thousands of cellular channels through the structure, allowing for a large surface area. The inside surface of the channels was coated with a catalyst for conversion of polluting fuel combustion products into less harmful emissions such as carbon dioxide (CO_2), nitrogen and water vapor.

The ceramic substrate used a platinum catalyst and required the removal of lead from gasoline to avoid poisoning the catalyst. The substrate technology served two purposes: to reduce pollutants from the fuel combustion process by 95% and to reduce lead pollution. Today, every car company relies on ceramic technology to control exhaust emissions and the fundamental ceramic technology extends to substrates for trucks, buses, passenger vehicles and other similar applications. Since the 1970s, vehicles employing advanced emissions control through catalyst conversion have reduced pollutants by over 3 Bt worldwide.[79]

Lachman, Bagley and Lewis were inducted into the National Inventors Hall of Fame in 2002 and received the National Medal of Technology in 2003.[80]

LARRY EVANS

Larry Evans, Professor of chemical engineering at the Massachusetts Institute of Technology (MIT), is known as the founder of ASPEN Technology. In 1976, Evans led the Advanced System for Process Engineering (ASPEN) project as the principal investigator; founding Aspen Technology in 1981 after the project was completed.[81] The ASPEN Project was a major research and development project initiated in response to the energy crises in the 1970s and funded at the cost of $6 million by the U.S. Department of Energy (DOE) and 65 other companies in the process industry across the world.[81] The objective of the project was to develop a third-generation process modeling and simulation system to create a state-of-the-art process simulator with advanced infrastructure and capabilities for any process industry. The project focused particularly on the technical and economic evaluation of proposed synthetic fuel processes.

Evans and his collaborators had a vision that computer-aided automation should be applied to chemical engineering. The potential application of that vision was in process engineering and manufacturing—the energy, chemicals and other industries that use a chemical process. This vision found an opportunity when market requirements changed following the oil shock and economic and political disruptions caused by it, which led to the creation of the Energy Laboratory at MIT.

Professor Evans built a team comprised of engineers, project faculty professional staff, post-docs and students, to develop software solutions to solve complex chemical engineering problems. The purpose of the ASPEN project was to develop a general process simulation system that could be used by chemical engineers across the process industries. The project resulted in a next-generation simulator that could simulate complex processes for highly non-ideal mixtures, solids, electrolytes, multiphase systems, chemicals, coal conversions and synthetic fuel processes. In 1981, Evans and seven key members of his team founded Aspen Technology to license the technology from MIT and to further develop and commercialize it.[82] Evans led the company as the Chief Executive Officer (CEO), fulfilling the company's mission to provide cutting-edge software-based process engineering tools and technologies to enable processes engineers to design new processes and improve efficiency and productivity of existing plants.

Under his leadership, the company grew into the leading supplier of engineering, manufacturing and supply chain software. The goal of the company focused on process optimization and eventually broadened to include asset optimization and management. Evans has received several prestigious awards recognizing his performance and leadership at AspenTech. He was inducted

into the National Academy of Engineering, named a high-technology Entrepreneur of the Year by Ernst & Young, and named a "Hero of Manufacturing" by FORTUNE magazine.[82]

HAREN S. GANDHI

Haren S. Gandhi was an engineer and an inventor who is known for his work in the field of automotive exhaust catalysts. While still attending the University of Detroit, he joined the Ford Motor Co. as a research scientist and dedicated his research to advanced emissions control. He began his research in areas such as three-way catalysts (TWCs) which convert carbon monoxide to CO_2 and hydrocarbons to CO_2, nitrogen and water. Gandhi employed precious metal utilization and recycling to reduce the use of the most used catalysts (platinum, palladium and rhodium). Gandhi's research also showed evidence of catalytic poisoning from lead and helped hasten the ban of leaded gasoline.

Gandhi earned 61 patents and has received numerous awards, including the U.S. National Medal of Technology and Innovation in 2002.[83] He was elected to the National Academy of Engineering (NAE) in 1999.[83] He was one of the few employees designated as Henry Ford Technical Fellow. In 2010, the Ford Motor Co. introduced the Haren Gandhi Research and Innovation Awards to honor his contributions. He was inducted into the National Hall of Inventors in 2017.[84]

HEINO FINKELMANN

Heino Finkelmann is known for his work in liquid crystalline elastomers. Although the liquid crystal state was first observed in late 1800s, the first classical application of liquid crystal polymers (LCPs) was Kevlar. The primary driving force in developing LCPs was to incorporate them into displays. Finkelmann's proposal to insert a flexible spacer between the main and side chains of the LCs helped create different nematic, smectic and cholesteric LC phases of side-chain LCPs (SCLCPs) which are useful functional materials.

P.G. de Gennes proposed liquid crystal elastomers (LCEs) in 1975, and Finkelmann and coworkers synthesized and established the properties of LCEs in 1981.[85] LCEs caught the interest of researchers and industry alike. LCEs are highly responsive to heat, light and magnetic fields, and nanomaterials additives have been used to tailor the LCEs properties to generate response to specific stimuli. LCE films can be used as optical retarders, in 3D glasses, patterned retarders for transflective displays and flat-panel LC displays.

Finkelmann received several awards and honors including the Duisberg Memorial Prize from the Society of German Chemists in 1984, the Gay-Lussac Humboldt Price in 2000, Agilent technologies Europhysics prize of the European Physical Society in 2003, and the George William Gray medal of the British Liquid Crystal Society in 2006.[86]

LEO BAEKELAND

Leo Baekeland was a Belgian-American chemist who is best known for the invention of Velox photographic paper in 1893 and Bakelite in 1907.[87] He is called the father of the plastics industry due to his introduction of Bakelite, the world's first synthetic plastic which marked the introduction of the Polymer Age.

Baekeland invented a process to develop photographic plates using water instead of other chemicals, patenting his technology in 1887. By 1891, he set up his own business working as a consulting chemist but returned to his old interest of producing paper that will enable enlarged pictures to be printed in artificial light. He successfully produced the first commercially successful photographic paper, Velox. He partnered with Leonard Jacobi and the Nepera Chemical Co. to commercialize his new product. The sales of Nepera to Eastman Kodak in 1899 enabled Baekeland to have enough funds to set up his own laboratory in New York. Baekeland developed a stronger diaphragm cell for a chloralkali electrolysis process. His contribution to an improved electrolysis cell was significant in that it led to the founding of the Hooker Chemical Co.

After the success of Velox, Baekeland was ready for a new project in chemical development and chose the field of synthetic resins. He followed the experimental results of Adolf von Baeyer and his failure in crystallizing, purifying or utilizing the 'black guck' these reactions produced. He began his own experiments while precisely controlling and studying the effects of temperature, pressure, molecular ratios and types of reactants used.

His first successful application was a synthetic replacement of shellac which he named Novolak. Although Baekeland determined that its properties were inferior and it failed commercially, it is still used as a photoresist. As Baekeland continued to experiment with various combinations of phenol and formaldehyde, he eventually produced a moldable plastic, Bakelite.

Bakelite was the first plastic that formed the class of plastics called thermosets. Due to the excellent heat resistance and electrical insulation properties of Bakelite, immediate commercial applications included radios, telephones and electrical insulators. Other notable advantages of Bakelite are its non-inflammable and inexpensive nature despite being more versatile in applications than other plastics. Since its invention, it has been used in a wide array of applications from engine parts to jewelry and electronics.

He received several awards and recognitions including the Perkin Medal in 1916, the Franklin medal in 1940 and was inducted into the National Inventors Hall of Fame in 1978.[88] He earned more than 100 patents and was awarded honorary degrees from the Universities of Pittsburgh and Edinburgh. HP

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